CHAPTER 8

CHANNELS

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8.1 INTRODUCTION

8.1.1 Definitions

Open channels are a natural or constructed conveyance for water in which:

- the water surface is exposed to the atmosphere, and
- the gravity force component in the direction of motion is the driving force.

There are various types of open channels encountered by the designer of transportation facilities:

- stream channel,
- roadside channel or ditch,
- irrigation channel, and
- drainage ditch.

The principles of open channel flow hydraulics are applicable to all drainage facilities including culverts and storm drains.

Stream channels are:

- usually natural channels with their size and shape determined by natural forces,

- usually compound in cross section with a main channel for conveying low flows and a floodplain to transport flood flows, and

- usually shaped in cross section and plan form by the long-term history of sediment load and water discharge that they experience.

Artificial channels include roadside channels, irrigation channels and drainage ditches, which are:

- constructed channels with regular geometric cross sections, and
- unlined or lined with artificial or natural material to protect against erosion.

Although the principles of open-channel flow are the same regardless of the channel type, stream channels and artificial channels (primarily roadside channels) will be treated separately in this Chapter as needed.

8.1.2 Significance

Channel analysis is necessary for the design of transportation drainage systems to assess:

- potential flooding caused by changes in water surface profiles,
- disturbance of the channel system upstream and/or downstream of the highway right-of-way,
- changes in lateral flow distributions,
- changes in velocity or direction of flow,
- need for conveyance and disposal of excess runoff, and
- need for channel lining to prevent erosion.

8.1.3 Design

Hydraulic design associated with natural channels and roadway ditches is a process that selects and evaluates alternatives according to established criteria. These criteria are the standards established by the Department to ensure that a highway facility meets its intended purpose without endangering the structural integrity of the facility itself and without undue adverse effects on the environment or the public welfare. An overview of the Hydraulic Analysis and Design of Open Channels can be found in Chapter 6 of Reference *(1)*.

8.1.4 Purpose

The purpose of this Chapter is to:

- establish UDOT's policy,
- specify design criteria,
- review design philosophy,
- outline channel design procedures, and
- demonstrate design techniques by example problems.

8.1.5 Symbols

To provide consistency within this Chapter and throughout this *Manual*, the symbols given in Table 8-1 will be used. These symbols were selected because of their wide use in channel hydraulics.

8.2 POLICY

8.2.1 General

Policy is a set of goals that establish a definite course or method of action and that are selected to guide and determine present and future decisions (see Policy Chapter). Policy is implemented through design criteria established as standards for making decisions (see Section 8.3).

8.2.2 Federal Policy

Federal policies are:

- Channel designs and/or designs of highway facilities that impact channels shall satisfy the policies of FHWA applicable to floodplain management if Federal funding is involved.

- FEMA floodway regulations and USACE wetland restrictions for permits shall be satisfied.

TABLE 8-1 — Symbols and Definitions

Symbol	Definition	Units
A	Cross sectional area	ft^2
B, b	Bottom width	ft
d	Depth of flow	ft
d_c	Critical depth of flow	ft
D_{50}, d_{50}	Median diameter of riprap, or median grain size	in
E	Specific Energy	ft
Fr	Froude Number	-
g	Acceleration due to gravity	ft/s^2
h	Stage (water surface height)	ft
h_l	Head loss	ft
K	Conveyance capacity	ft^3/s
k_m	Contraction or Expansion loss coefficient	-
L	Channel reach length	f
n	Manning's roughness coefficient	-
P	Wetted perimeter	f
Q, q	Flow rate	ft^3/s
R	Hydraulic radius (A/P)	ft
S	Energy gradeline slope	ft/ft
T	Channel top width	ft
V	Velocity of flow	ft/s
v_c	Critical velocity	ft/s
Y, y	Depth of flow	ft
y_c	Critical depth	ft
z	Elevation head	ft
z	Horizontal distance	ft
γ	Unit weight of water	lb/ft^3
τ	Shear stress (Tractive force)	lb/ft^2
τ_p	Permissible shear stress	lb/ft^2
α	Velocity distribution coefficient	-
θ	Channel slope angle	° (degrees)

8.2.3 Agency Policy

- Coordination with other Federal, State and local agencies concerned with water resources planning shall have high priority in the planning of highway facilities.

- Safety of the general public shall be an important consideration in the selection of cross-sectional geometry of artificial drainage channels.

- The design of artificial drainage channels or other facilities shall consider the frequency and type of maintenance expected and make allowance for access of maintenance equipment.

- A stable channel is the goal for all channels that are located on highway right-of-way or that impact highway facilities.

- Environmental impacts of channel modifications, including disturbance of fish habitat, wetlands and channel stability, shall be assessed.

- The range of design channel discharges shall be selected and approved by the designer based on class of roadway, consequences of traffic interruption, flood-hazard risks, economics and local site conditions.

8.3 DESIGN CRITERIA

8.3.1 General

Design criteria establish the standards by which a policy is placed into action. They form the basis for the selection of the final design configuration. Listed below are examples of design criteria that shall be considered for channel design.

8.3.2 Stream Channels

The following criteria apply to natural channels and may be revised as approved by the Department Hydraulic Engineer (Region or Central):

- The hydraulic effects of floodplain encroachments shall be evaluated over a full range of frequency-based peak discharges, from the 2-yr through 500-yr recurrence intervals, on any major highway facility as deemed necessary by the designer.

- If relocation of a stream channel is unavoidable, the cross-sectional shape, meander, pattern, roughness, sediment transport and slope shall conform to the existing conditions as practicable. The designer shall investigate the need for energy dissipation and apply appropriate measures where practical.

- Streambank stabilization shall be provided, when appropriate, as a result of any stream disturbance such as encroachment and shall include both upstream and downstream banks and the local site.

8.3.3 Roadside Channels

The following criteria apply to roadside channels and may be revised as approved by the Department Hydraulic Engineer (Region or Central):

- Channel side slopes shall not exceed the angle of repose of the soil and/or lining and shall be 1V:2H or flatter in the case of rock-riprap lining.
- Flexible linings shall be designed according to the method of allowable tractive force.
- The design discharge for permanent roadside ditch linings shall have a 10-yr frequency, and temporary linings shall be designed for the 2-yr frequency flow.
- Channel freeboard shall be 1 ft or two velocity heads, whichever is larger.

8.4 OPEN CHANNEL FLOW

8.4.1 General

Design analysis of both natural and artificial channels proceeds according to the basic principles of open-channel flow (see References *(7)*, *(18)*). The basic principles of fluid mechanics — continuity, momentum and energy — can be applied to open-channel flow with the additional complication that the position of the free surface is usually one of the unknown variables. The determination of this unknown is one of the principal (or primary) objectives of open-channel flow analysis.

8.4.2 Definitions

8.4.2.1 Specific Energy

Specific energy, E, is defined as the energy head relative to the channel bottom. See Figure 8-1 for a plot of the specific energy diagram. If the channel is not too steep (slope less than 10%) and the streamlines are nearly straight and parallel (so that the hydrostatic assumption holds), the specific energy E becomes the sum of the depth and velocity head:

$$E = y + \alpha\,(V^2/2g) \qquad (8.1)$$

where:
- y = depth, ft
- α = velocity distribution coefficient (see Equation 8.2)
- V = mean velocity, ft/s
- g = gravitational acceleration, 32.2 ft/s^2

The velocity distribution coefficient is taken to have a value of one for turbulent flow in prismatic channels but may be significantly different than one in natural channels.

8.4.2.2 Velocity Distribution Coefficient

The flow velocity may not be uniform in a channel cross section due to the presence of free surface, friction along the channel boundary, and change in alignment and cross section. As a result of nonuniform distribution of velocities in a channel section, the velocity head of an open channel is usually greater than the average velocity head computed as $(Q/A_t)^2/2g$. A weighted average value of the velocity head is obtained by multiplying the average velocity head, above, by a velocity distribution coefficient, α, defined as:

$$\alpha = \frac{\sum_{i=1}^{n} (K_i^3 / A_i^2)}{(K_t^3 / A_t^2)} \tag{8.2}$$

where:
K_i = conveyance in subsection (see Equation 8.8), ft^3/s
K_t = total conveyance in section (see Equation 8.8), ft^3/s
A_i = cross-sectional area of subsection, ft^2
A_t = total cross-sectional area of section, ft^2
n = number of subsections

8.4.2.3 Energy Gradeline

The total head is the specific energy head plus the elevation of the channel bottom with respect to some datum. The locus of the total head from one cross section to the next defines the energy gradeline.

8.4.2.4 Steady and Unsteady Flow

A steady flow is one in which the discharge passing a given cross section is constant with respect to time. The maintenance of steady flow in any reach requires that the rates of inflow and outflow be constant and equal. When the discharge varies with time, the flow is unsteady.

8.4.2.5 Uniform Flow and Non-uniform Flow

A non-uniform flow is one in which the velocity and depth vary in the direction of motion, while they remain constant in uniform flow. Uniform flow can only occur in a prismatic channel, which is a channel of constant cross section, roughness and slope in the flow direction; however, non-uniform flow can occur either in a prismatic channel or in a natural channel with variable properties.

8.4.2.6 Gradually Varied and Rapidly Varied Flow

A non-uniform flow in which the depth and velocity change gradually enough in the flow direction that vertical accelerations can be neglected is referred to as a gradually varied flow; otherwise, it is considered to be rapidly varied.

8.4.2.7 Froude Number

The Froude number, Fr, represents the ratio of inertial forces to gravitational forces and is defined by:

$$Fr = \frac{V}{(gd \cos \theta / \alpha)^{0.5}} \tag{8.3}$$

where:
α = velocity distribution coefficient
V = mean velocity = Q/A, ft/s
g = acceleration of gravity, 32.2 ft/s^2
d = hydraulic depth = A/T, ft
A = cross-sectional area of flow, ft^2
T = channel topwidth at the water surface, ft
Q = total discharge, ft^3/s
θ = channel slope angle, ft/ft

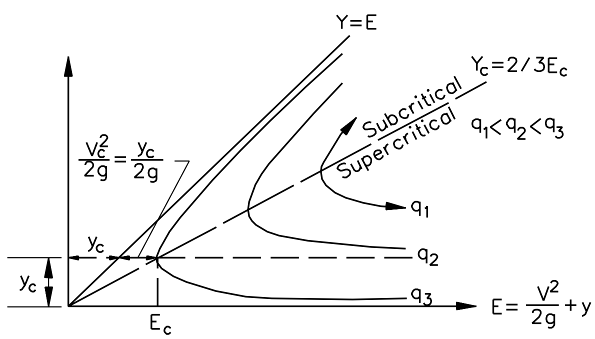
This expression for Froude number applies to any open channel or channel subsection with uniform or gradually varied flow. For rectangular channels, the hydraulic depth is equal to the flow depth.

8.4.2.8 Critical Flow

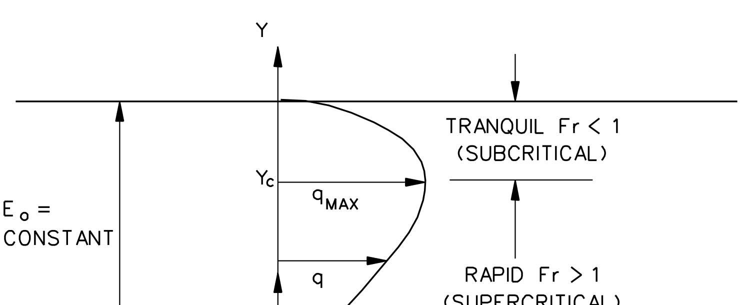
Critical flow occurs when the specific energy is a minimum for a given discharge in regular channel cross sections. The depth at which the specific energy is a minimum is called critical depth. At critical depth, the Froude number has a value of one. Critical depth is also the depth of maximum discharge when the specific energy is held constant. These relationships are illustrated in Figure 8-1. During critical flow, the velocity head is equal to half the hydraulic depth. The general expression for flow at critical depth is:

$$\alpha\, Q^2/g = A^3/T \tag{8.4}$$

where:
- α = velocity distribution coefficient
- Q = total discharge, ft^3/s
- g = gravitational acceleration, 32.2 ft/s^2
- A = cross-sectional area of flow, ft^2
- T = channel topwidth at the water surface, ft



(a) Specific Energy Diagram



(b) Discharge Diagram

FIGURE 8-1 — Specific Energy and Discharge Diagram for Rectangular Channels

(Adopted from HDS No. 6 *(14)*)

When flow is at critical depth, Equation 8.4 must be satisfied, no matter what the shape of the channel.

8.4.2.9 Subcritical Flow

Depths greater than critical depth occur in subcritical flow, and the Froude number is less than one. In this state of flow, small water surface disturbances can travel both upstream and downstream, and the control is always located downstream.

8.4.2.10 Supercritical Flow

Depths less than critical depth occur in supercritical flow, and the Froude number is greater than one. Small water surface disturbances are always swept downstream in supercritical flow, and the location of the flow control is always upstream.

8.4.2.11 Hydraulic Jump

A hydraulic jump occurs as an abrupt transition from supercritical to subcritical flow in the flow direction. There are significant changes in depth and velocity in the jump, and energy is dissipated. For this reason, the hydraulic jump is often employed to dissipate energy and control erosion at highway drainage structures.

A hydraulic jump will not occur until the ratio of the flow depth (y_1) in the approach channel to the flow depth (y_2) in the downstream channel reaches a specific value that depends on the channel geometry. The depth before the jump is called the initial depth (y_1), and the depth after the jump is the sequent depth (y_2). When a hydraulic jump is used as an energy dissipator, controls to create sufficient tailwater depth are often necessary to control the location of the jump and to ensure that a jump will occur during the desired range of discharges. Sills can be used to control a hydraulic jump if the tailwater depth is less than the sequent depth. If the tailwater depth is higher than the sequent depth, a drop in the channel floor must be used to ensure a jump (see References *(7)*, *(12)*).

8.4.3 Flow Classification

The classification of open-channel flow can be summarized as follows:

Steady Flow

1. Uniform Flow
2. Non-uniform Flow

    a. Gradually Varied Flow
    b. Rapidly Varied Flow

Unsteady Flow

1. Unsteady Uniform Flow (rare)
2. Unsteady Non-uniform Flow

    a. Gradually Varied Unsteady Flow
    b. Rapidly Varied Unsteady Flow

The steady, uniform flow case and the steady, non-uniform flow case are the most fundamental types of flow treated in highway engineering hydraulics.

8.4.4 Equations

The following equations are those most commonly used to analyze open channel flow. The use of these equations in analyzing open channel hydraulics is discussed in Section 8.5.

8.4.4.1 Continuity Equation

The continuity equation is the statement of conservation of mass in fluid mechanics. For the special case of one-dimensional, steady flow of an incompressible fluid, it assumes the simple form:

$$Q = A_1V_1 = A_2V_2 \tag{8.5}$$

where: Q = discharge, ft^3/s

A = cross-sectional area of flow, ft^2

V = mean cross-sectional velocity, ft/s (which is perpendicular to the cross section)

The subscripts 1 and 2 refer to successive cross sections along the flow path.

8.4.4.2 Manning's Equation

For a given depth of flow in an open channel with a steady, uniform flow, the mean velocity, V, can be computed with Manning's equation:

$$V = (1.486/n)R^{2/3}S^{1/2} \quad (8.6)$$

where:

V = velocity, ft/s

n = Manning's roughness coefficient

R = hydraulic radius = A/P, ft

P = wetted perimeter, ft

S = slope of the energy gradeline, ft/ft (Note: For steady uniform flow, S = channel slope, ft/ft)

The selection of Manning's n is generally based on observation; however, considerable experience is essential in selecting appropriate n values. The selection of Manning's n is discussed in Section 8.5.2.1. The range of n values for various types of channels and floodplains is given in Table 8-2.

The continuity equation can be combined with Manning's equation to obtain the steady, uniform flow discharge as:

$$Q = (1.486/n)AR^{2/3}S^{1/2} \quad (8.7)$$

TABLE 8-2 — Values of Manning's Roughness Coefficient n (Uniform Flow)

Type of Channel and Description	Minimum	Normal	Maximum
EXCAVATED OR DREDGED			
1. Earth, straight and uniform			
a. Clean, recently completed	0.016	0.018	0.020
b. Clean, after weathering	0.018	0.022	0.025
c. Gravel, uniform section, clean	0.022	0.025	0.030
d. With short grass, few weeds	0.022	0.027	0.033
2. Earth, winding and sluggish			
a. No vegetation	0.023	0.025	0.030
b. Grass, some weeds	0.025	0.030	0.033
c. Dense weeds or aquatic plans in deep channels	0.030	0.035	0.040
d. Earth bottom and rubble sides	0.025	0.030	0.035
e. Stony bottom and weedy sides	0.025	0.035	0.045
f. Cobble bottom and clean sides	0.030	0.040	0.050
3. Dragline-excavated or dredged			
a. No vegetation	0.025	0.028	0.033
b. Light brush on banks	0.035	0.050	0.060
4. Rock cuts			
a. Smooth and uniform	0.025	0.035	0.040
b. Jagged and irregular	0.035	0.040	0.050
5. Channels not maintained, weeds and brush uncut			
a. Dense weeds, high as flow depth	0.050	0.080	0.120
b. Clean bottom, brush on sides	0.040	0.050	0.080
c. Same, highest stage of flow	0.045	0.070	0.110
d. Dense brush, high stage	0.080	0.100	0.140
NATURAL STREAMS			
1. Minor streams (top width at flood stage < 30 m)			
a. Streams on Plain			
1) Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
2) Same as above, but more stones/weeds	0.030	0.035	0.040
3) Clean, winding, some pools/shoals	0.033	0.040	0.045
4) Same as above, but some weeds/stones	0.035	0.045	0.050
5) Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
6) Same as 4, but more stones	0.045	0.050	0.060
7) Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
8) Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
b. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
1) Bottom: gravels, cobbles and few boulders	0.030	0.040	0.050
2) Bottom: cobbles with large boulders	0.040	0.050	0.070

TABLE 8-2 — Values of Manning's Roughness Coefficient n (Uniform Flow) (continued)

Type of Channel and Description	Minimum	Normal	Maximum
2. Floodplains			
a. Pasture, no brush			
1) Short grass	0.025	0.030	0.035
2) High grass	0.030	0.035	0.050
b. Cultivated area			
1) No crop	0.020	0.030	0.040
2) Mature row crops	0.025	0.035	0.045
3) Mature field crops	0.030	0.040	0.050
c. Brush			
1) Scattered brush, heavy weeds	0.035	0.050	0.070
2) Light brush and trees, in winter	0.035	0.050	0.060
3) Light brush and trees, in summer	0.040	0.050	0.080
4) Medium to dense brush, in winter	0.045	0.070	0.110
5) Medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
1) Dense willows, summer, straight	0.110	0.150	0.200
2) Cleared land with tree stumps, no sprouts	0.030	0.040	0.050
3) Same as above, but with heavy growth of sprouts	0.050	0.060	0.080
4) Heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
5) Same as above, but with flood stage reaching branches	0.100	0.120	0.160
3. Major Streams (top width at flood stage > 30 m)			
a. Regular section with no boulders or brush	0.025	—	0.060
b. Irregular and rough section	0.035	—	0.100

Source: Reference *(7)*.

The conveyance represents the carrying capacity of a stream cross section based upon its geometry and roughness characteristics alone and is independent of the streambed slope.

The concept of channel conveyance is useful when computing the distribution of overbank flood flows in the stream cross section and the flow distribution through the opening in a proposed stream crossing. It is also used to determine the velocity distribution coefficient, α (see Equation 8.2).

For a given channel geometry, slope and roughness and a specified value of discharge Q, a unique value of depth occurs in steady, uniform flow. It is called normal depth and is computed from Equation 8.7 by expressing the area and hydraulic radius in terms of depth. The resulting equation may require a trial-and-error solution. See Section 8.5.3 for a more detailed discussion of the computation of normal depth.

If the normal depth is greater than critical depth, the slope is classified as a mild slope while, on a steep slope, the normal depth is less than critical depth. Thus, uniform flow is subcritical on a mild slope and supercritical on a steep slope.

8.4.4.3 Conveyance

In channel analysis, it is often convenient to group the channel cross section properties in a single term called the channel conveyance K:

$$K = (1.486/n)AR^{2/3} \tag{8.8}$$

and then Equation 8.7 can be written as:

$$Q = KS^{1/2} \tag{8.9}$$

8.4.4.4 Energy Equation

The energy equation expresses conservation of energy in open channel flow expressed as energy per unit weight of fluid, which has dimensions of length and is therefore called energy head. The energy head is composed of potential energy head (elevation head), pressure head, and kinetic energy head (velocity head). These energy heads are scalar quantities that give the total energy head at any cross section when added. Written between an upstream open channel cross section designated 1 and a downstream cross section designated 2 (see Figure 8-2), the energy equation is:

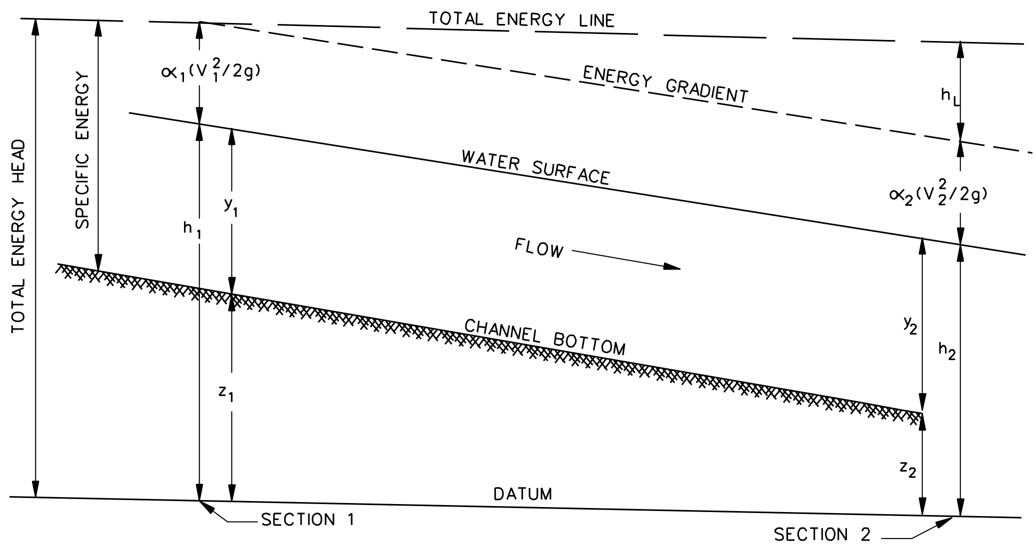
$$h_1 + \alpha_1 (V_1^2/2g) = h_2 + \alpha_2 (V_2^2/2g) + h_L \tag{8.10}$$

where: h_1, h_2 = the upstream and downstream stages, respectively, ft

α = velocity distribution coefficient

V = mean velocity, ft/s

h_L = head loss due to local cross-sectional changes (minor loss) and boundary resistance, ft



Source: HDS No. 6 *(14)*.

FIGURE 8-2 — Terms in the Energy Equation

The stage, h, is the sum of the elevation head, z, at the channel bottom and the pressure head or depth of flow, y; i.e., $h = z + y$. The terms in the energy equation are illustrated graphically in Figure 8-2. The energy equation states that the total energy head at an upstream cross section is equal to the energy head at a downstream section plus the intervening energy head loss. The energy equation can only be applied between two cross sections at which the streamlines are nearly straight and parallel so that vertical accelerations can be neglected

8.5 HYDRAULIC ANALYSIS

8.5.1 General

The hydraulic analysis of a channel determines the depth and velocity at which a given discharge will flow in a channel of known geometry, roughness and slope. The depth and velocity of flow are necessary for the design or analysis of channel linings and highway drainage structures.

Two methods are commonly used in hydraulic analysis of open channels. The single-section method is a simple application of Manning's equation to determine tailwater rating curves for culverts or to analyze other situations in which uniform or nearly uniform flow conditions exist. Manning's equation can be used to estimate high-water elevations for bridges that do not constrict the flow. The step-backwater method is used to compute the complete water surface profile in a stream reach to evaluate the unrestricted water surface elevations for bridge hydraulic design or to analyze other gradually varied flow problems in streams.

The single-section method will generally yield less reliable results because it requires more judgment and assumptions than the step-backwater method. In many situations, however, the single-section method is all that is justified (e.g., a standard roadway ditch, culverts, storm drain, outfalls).

Occasionally, the designer may need to use a more detailed method of analysis than the single-section method or the computation of a water surface profile using the step-backwater method. Special analysis techniques include two-dimensional analysis, water and sediment routing, and unsteady flow analysis.

8.5.2 Cross Sections

Cross-sectional geometry of streams is defined by coordinates of lateral distance and ground elevation that locate individual ground points. The cross section is taken normal to the flow direction along a single, straight line where possible but, in wide floodplains or bends, it may be necessary to use a section along intersecting straight lines; i.e., a "dog-leg" section. It is especially important to make a plot of the cross section to reveal any inconsistencies or errors.

Cross sections should be located to be representative of the subreaches between them. Stream locations with major breaks in bed profile, abrupt changes in roughness or shape, control sections such as free overfalls, bends and contractions, or other abrupt changes in channel slope or conveyance will require cross sections taken at shorter intervals to better model the change in conveyance.

Cross sections should be subdivided with vertical boundaries where there are abrupt lateral changes in geometry and/or roughness as for overbank flows. The conveyances of each subsection are computed separately to determine the flow distribution and are then added to determine the total flow conveyance. The subsection divisions must be chosen carefully so that the distribution of flow or conveyance is nearly uniform in each subsection (Reference *(9)*). Selection of cross sections and the vertical subdivision of a cross section are shown in Figure 8-3.

8.5.2.1 Manning's n Value Selection

Manning's n is affected by many factors and its selection in natural channels depends heavily on engineering experience. Pictures of channels and floodplains for which the discharge has been measured and Manning's n has been calculated are very useful (see References *(2)*, *(3)*). For situations lying outside the engineer's experience, a more regimented approach is presented in Reference *(2)*. Once the Manning's n values have been selected, it is highly recommended that they be verified or calibrated with historical high-water marks and/or gaged streamflow data.

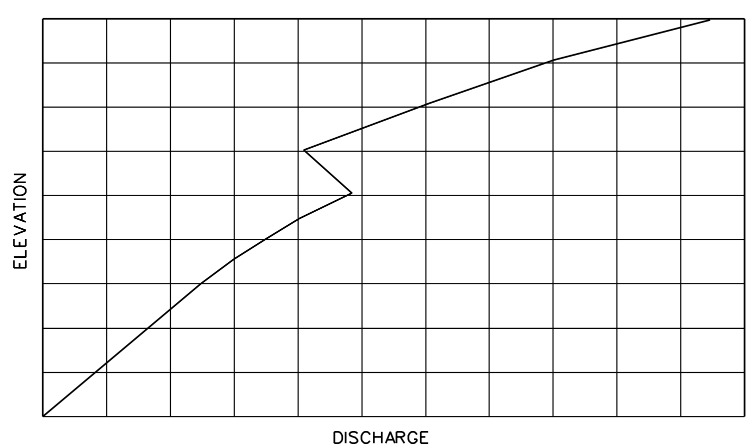
Manning's n values for artificial channels are more easily defined than for natural stream channels. Table 8-2 lists typical n values of both artificial channels and natural stream channels.

8.5.2.2 Calibration

The equations should be calibrated with historical high-water marks and/or gaged streamflow data to ensure that they accurately represent local channel conditions. The following parameters, in order of preference, should be used for calibrations: Manning's n, slope, discharge and cross section. Proper calibration is essential if accurate results are to be obtained.

8.5.2.3 Switchback Phenomenon

If the cross section is improperly subdivided, the mathematics of Manning's equation causes a switchback. A switchback results where the calculated discharge decreases with an associated increase in elevation. This occurs when, with a minor increase in water depth, there is a large increase of wetted perimeter. Simultaneously, there is a corresponding small increase in cross-sectional area that causes a net decrease in the hydraulic radius from the value it had for a lesser water depth. With the combination of the lower hydraulic radius and the slightly larger cross-sectional area, a discharge is computed that is lower than the discharge based upon the lower water depth. More subdivisions within such cross sections should be used to avoid the switchback.



SWITCHBACK

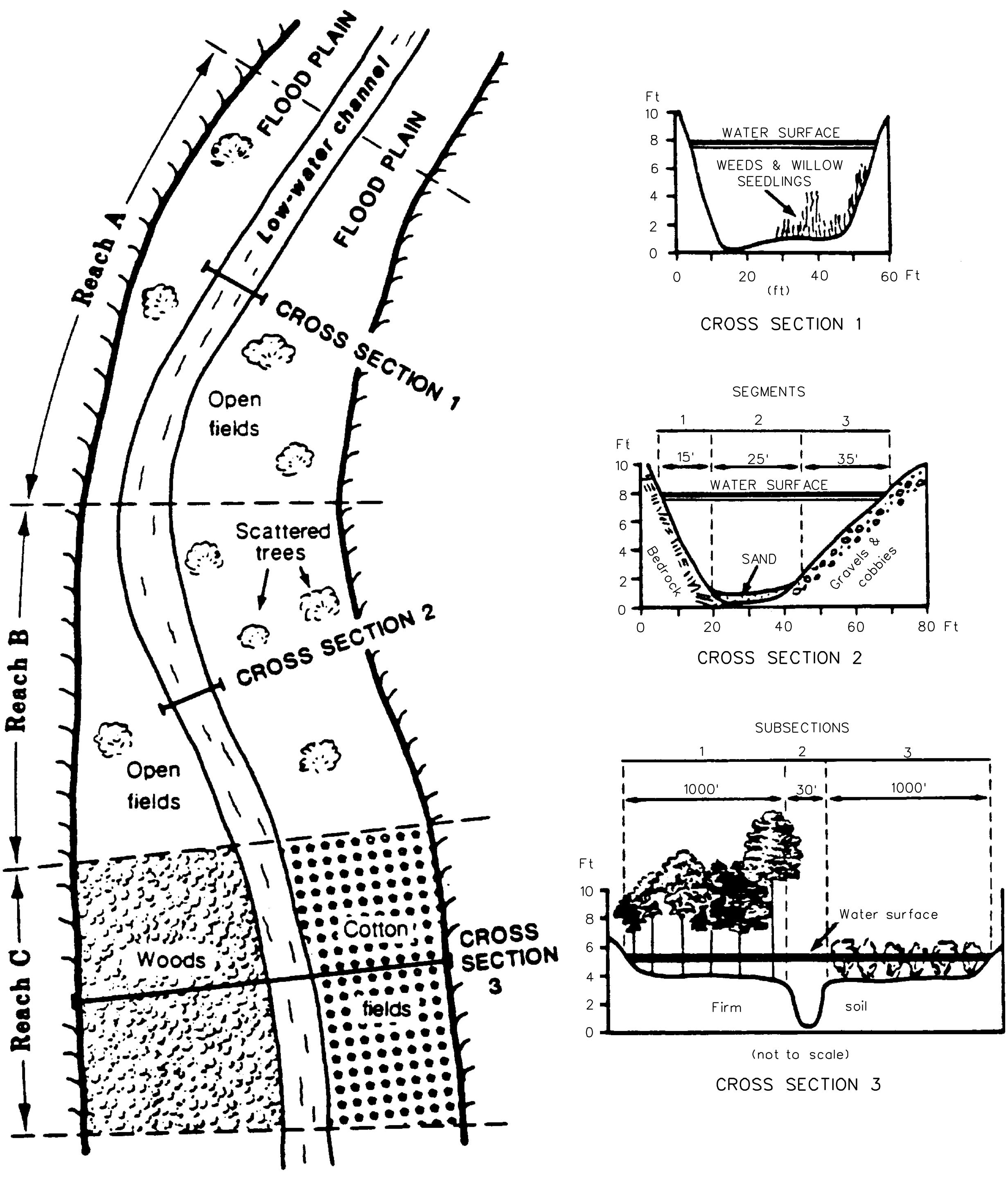


FIGURE 8-3 — Hypothetical Cross Section Showing Reaches, Segments and Subsections Used In Assigning n Values

Source: Reference *(2)*.

This phenomenon can occur in any type of conveyance computation, including the step-backwater method. Computer logic can be seriously confused if a switchback were to occur in any cross section being used in a step-backwater program. For this reason, the cross section should always be subdivided with respect to both vegetation and geometric changes. Note that the actual n-value itself may be the same in adjacent subsections.

8.5.3 Single-Section Analysis

The single-section analysis method (slope-area method) is simply a solution of Manning's equation for the normal depth of flow given the discharge and cross section properties including geometry, slope and roughness. It implicitly assumes the existence of steady, uniform flow; however, uniform flow rarely exists in either artificial or natural stream channels. Nevertheless, the single-section method is often used to design artificial channels for uniform flow as a first approximation and to develop a stage-discharge rating curve in a stream channel for tailwater determination at a culvert or storm drain outlet.

A stage-discharge curve is a graphical relationship of streamflow depth or elevation to discharge at a specific point on a stream. This relationship should cover a range of discharges up to at least the base (100-yr) flood. The stage-discharge curve can be determined as follows:

- Select the typical cross section at or near the location where the stage-discharge curve is needed.
- Subdivide cross section and assign n-values to subsections as described in Section 8.5.2.1.
- Estimate water-surface slope. Because uniform flow is assumed, the average slope of the streambed can usually be used.
- Apply a range of incremental water surface elevations to the cross section.
- Calculate the discharge using Manning's equation for each incremental elevation. Total discharge at each elevation is the sum of the discharges from each subsection at that elevation. In determining hydraulic radius, the wetted perimeter should be measured only along the solid boundary of the cross section and not along the vertical water interface between subsections.
- After the discharge has been calculated at several incremental elevations, a plot of stage versus discharge should be made. This plot is the stage-discharge curve, and it can be used to determine the water surface elevation corresponding to the design discharge or other discharge of interest.

An example application of the stage-discharge curve procedure is presented in Appendix 8.A.

Alternatively, a graphical technique such as that given in Figure 8-4 or a nomograph as in Figure 8-5 can be used for trapezoidal and prismatic channels. The best approach, especially for stream channels, is to use a computer program such as WSPRO or HEC-RAS to obtain the normal depth.

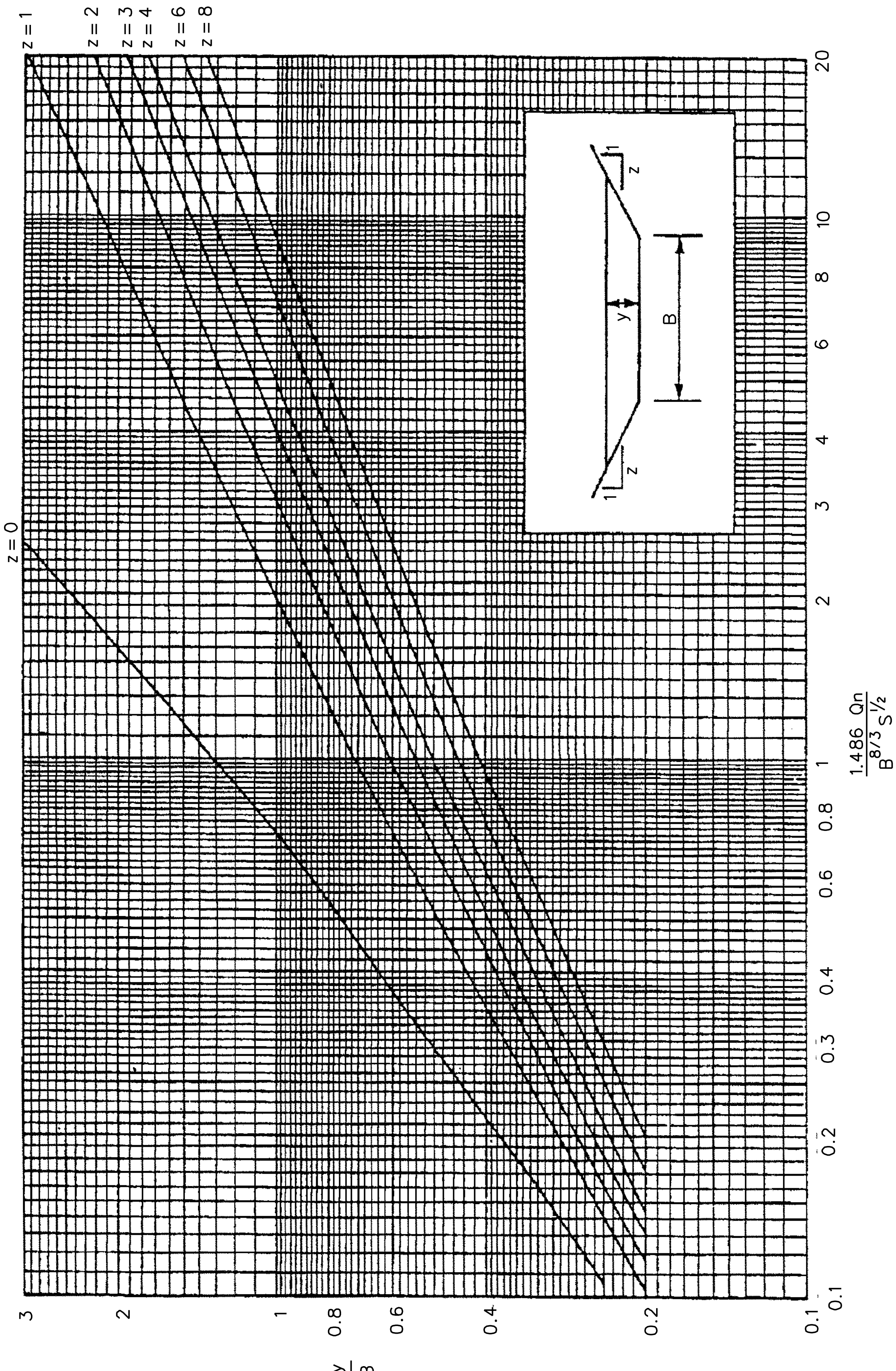


FIGURE 8-4 — Trapezoidal Channel Capacity Chart (7)

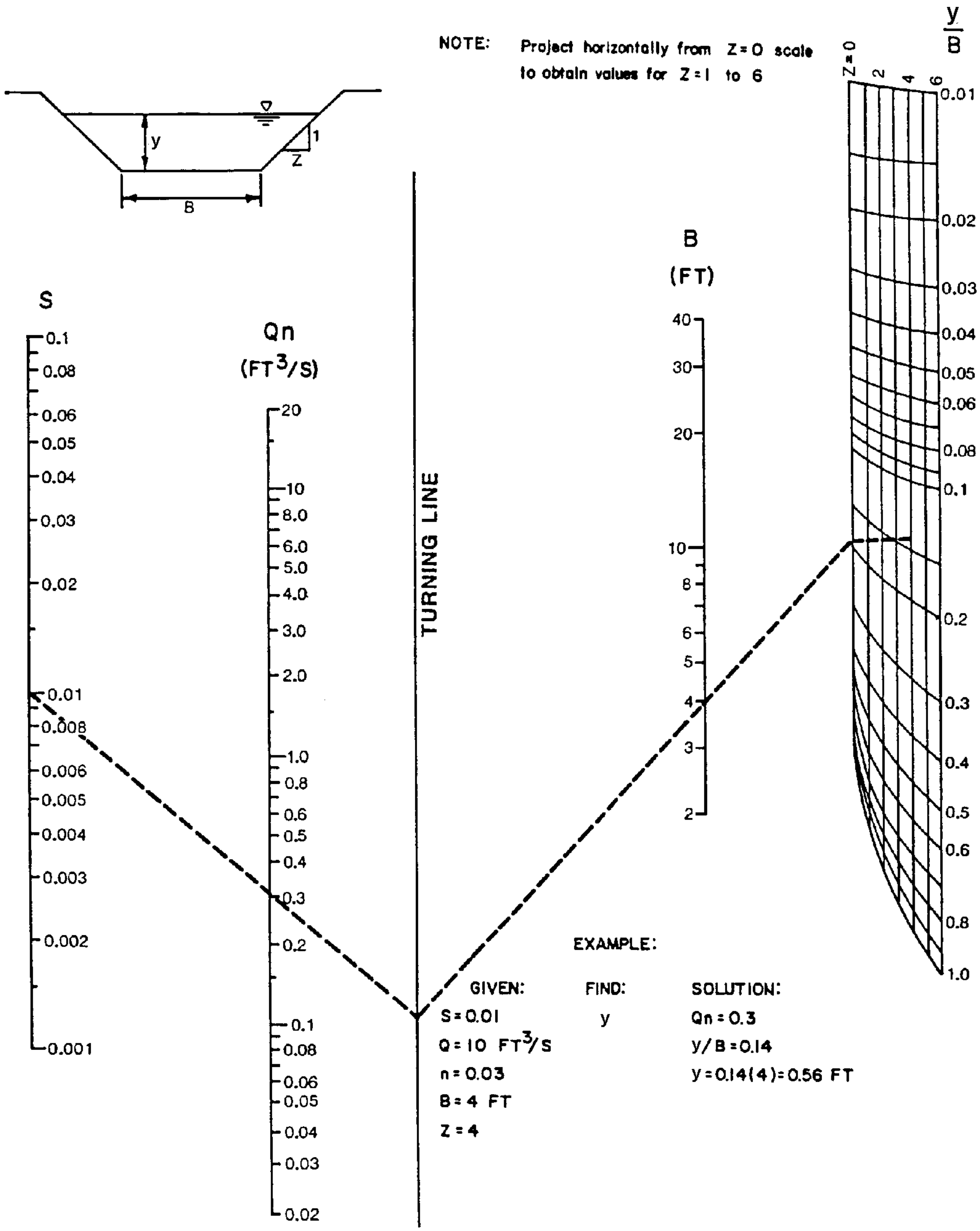


FIGURE 8-5 — Nomograph for Normal Depth

Source: HEC 15 *(11).*

In stream channels, the transverse variation of velocity in any cross section is a function of subsection geometry and roughness and may vary considerably from one stage and discharge to another. It is important to know this variation for designing erosion control measures and locating relief openings in highway fills, for example. The best method of establishing transverse velocity variations is by current meter measurements. If this is not possible, the single-section method can be used by dividing the cross section into subsections of relatively uniform roughness and geometry. It is assumed that the energy grade line slope is the same across the cross section so that the total conveyance K_t of the cross section is the sum of the subsection conveyances. The total discharge is then $K_t S^{1/2}$ and the discharge in each subsection is proportional to its conveyance. The velocity in each subsection is obtained from the continuity equation, V = Q/A.

Alluvial channels present a more difficult problem in establishing stage-discharge relations by the single-section method because the bed itself is deformable and may generate bed forms such as ripples and dunes in lower regime flows. These bed forms are highly variable with the addition of form resistance, and selection of a value of Manning's n is not straightforward. Instead, several methods outlined in Reference *(34)* have been developed for this case (Einstein-Barbarossa; Kennedy-Alam-Lovera; and Engelund) and should be followed unless it is possible to obtain a measured stage-discharge relation.

There may be locations where a stage-discharge relationship has already been measured in a channel. These usually exist at gaging stations on streams monitored by USGS. Measured stage-discharge curves will generally yield more accurate estimates of water surface elevation and should take precedence over the analytical methods described above.

8.5.4 Step-Backwater Analysis

Step-backwater analysis is useful for determining unrestricted water surface profiles where a highway crossing is planned and for analyzing how far upstream the water surface elevations are affected by a culvert or bridge. Because the calculations involved in this analysis are tedious and repetitive, it is recommended that a computer program such as the FHWA/USGS program WSPRO *(17)* or USACE HEC-RAS *(28-30)* be used. Special analysis techniques (see Section 8.5.5) should be considered for complex situations where a step-backwater analysis might not give the desired level of accuracy.

8.5.4.1 Step-Backwater Models

The WSPRO program has been designed to provide a water surface profile for six major types of open channel flow situations:

- unconstricted flow,
- single-opening bridge,
- bridge opening(s) with spur dikes,
- single-opening embankment overflow, and
- multiple alternatives for a single site and multiple openings.

The HEC-RAS program, developed by USACE, is widely used for calculating water surface profiles for steady, gradually varied flow in a natural or constructed channel. Both subcritical and supercritical flow profiles can be calculated. The effects of bridges, culverts, weirs and structures in the floodplain may be also considered in the computations. These programs are also designed for application in floodplain management and flood insurance studies.

8.5.4.2 Step-Backwater Methodology

The computation of water surface profiles by WSPRO and HEC-RAS is based on the standard-step method in which the stream reach of interest is divided into a number of subreaches by cross sections spaced such that the flow is gradually varied in each subreach. The energy equation is then solved in a step-wise fashion for the stage at one cross section based on the stage at the previous cross section.

The method requires definition of the geometry and roughness of each cross section as discussed in Section 8.5.1. Manning's n values can vary both horizontally across the section and vertically. Expansion and contraction head loss coefficients, variable main channel and overbank flow lengths, and the method of averaging the slope of the energy grade line can all be specified.

To amplify on the methodology, the energy equation is repeated from Section 8.4.4:

$$h_1 + \alpha_1 (V_1^2 / 2g) = h_2 + \alpha_2 (V_2^2 / 2g) + h_L \qquad (8.11)$$

where: h_1, h_2 = upstream and downstream stages, respectively, ft

α = velocity distribution coefficient

V = mean velocity, ft/s

h_L = head loss due to local cross-sectional changes (minor loss) and boundary resistance, ft

The stage h is the sum of the elevation head z at the channel bottom and the pressure head, or depth of flow, y; i.e., h = z + y. The energy equation is solved between successive stream reaches with nearly uniform roughness, slope and cross-sectional properties.

The total head loss is calculated from:

$$h_L = K_m \left| [(\alpha_1 V_1^2 / 2g) - (\alpha_2 V_2^2 / 2g)] \right| + \overline{S}_f L \qquad (8.12)$$

where: K_m = expansion or contraction loss coefficient

$\overline{S}_f$ = the mean slope of the energy grade line evaluated from Manning's equation and a selected averaging technique, ft/ft

L = discharge-weighted or conveyance-weighted reach length, ft

These equations are solved numerically in a step-by-step procedure called the Standard-Step Method from one cross section to the next.

The loss coefficient K_m is used to calculate the expansion or contraction loss between cross sections. Typical values for K_m are 0.1 for a gradual contraction, 0.3 for a sudden contraction, 0.3 for a gradual expansion and 0.5 for a sudden expansion. The default values of the minor loss coefficient K_m are 0.0 and 0.1 for contractions and 0.5 and 0.3 for expansions in WSPRO and HEC-RAS, respectively. Refer to the HEC-RAS *Hydraulic Reference Manual (29)* for guidance on selecting expansion and contraction loss coefficients.

WSPRO calculates a conveyance-weighted reach length, L, as:

$$L = [(L_{lob}K_{lob} + L_{ch}K_{ch} + L_{rob}K_{rob})/(K_{lob} + K_{ch} + K_{rob})] \tag{8.13}$$

where: L_{lob}, L_{ch}, L_{rob} = flow distance between cross sections in the left overbank, main channel and right overbank, respectively, ft

K_{lob}, K_{ch}, K_{rob} = conveyance in the left overbank, main channel and right overbank, respectively, of the cross section with the unknown water surface elevation

HEC-RAS calculates a discharge-weighted reach length, L, as:

$$L = [(L_{lob}\overline{Q}_{lob} + L_{ch}\overline{Q}_{ch} + L_{rob}\overline{Q}_{rob})/(\overline{Q}_{lob} + \overline{Q}_{ch} + \overline{Q}_{rob})] \tag{8.14}$$

where: L_{lob}, L_{ch}, L_{rob} = flow distance between cross sections in the left overbank, main channel and right overbank, respectively, ft

$\overline{Q}_{lob}, \overline{Q}_{ch}, \overline{Q}_{rob}$ = arithmetic average of flows between cross section for the left overbank, main channel and right overbank, respectively, ft^3/s

WSPRO and HEC-RAS allow the user the following options for determining the friction slope, $\overline{S}_f$:

- Average conveyance equation:

$$\overline{S}_f = [(Q_u + Q_d)/(K_u + K_d)]^2 \tag{8.15}$$

- Average friction slope equation:

$$\overline{S}_f = (S_{fu} + S_{fd})/2 \tag{8.16}$$

- Geometric mean friction slope equation:

$$\overline{S}_f = (S_{fu}S_{fd})^{1/2} \tag{8.17}$$

- Harmonic mean friction slope equation:

$$\overline{S}_f = (2S_{fu}S_{fd})/(S_{fu} + S_{fd}) \tag{8.18}$$

where: Q_u, Q_d = discharge at the upstream and downstream cross sections, respectively, ft^3/s

K_u, K_d = conveyance at the upstream and downstream cross sections, respectively, ft^3/s

S_{fu}, S_{fd} = friction slope at the upstream and downstream cross sections, respectively, ft/ft

The default option is the geometric mean friction slope equation in WSPRO and the average conveyance equation in HEC-RAS.

8.5.4.3 Profile Computation

Water surface profile computation requires a beginning value of elevation or depth (boundary condition) and proceeds upstream for subcritical flow and downstream for supercritical flow. In the case of supercritical flow, critical depth is often the boundary condition at the control section but, in subcritical flow, uniform flow and normal depth may be the boundary condition. The starting depth in this case can either be found by the single-section method (slope-area method) or by computing the water surface profile upstream to the desired location for several starting depths and the same discharge. These profiles should converge toward the desired normal depth at the control section to establish one point on the stage-discharge relation. If the several profiles do not converge, then the stream reach may need to be extended downstream, or a shorter cross section interval should be used, or the range of starting water surface elevations should be adjusted. In any case, a plot of the convergence profiles can be a very useful tool in such an analysis (see Figure 8-6).

Given a long enough stream reach, the water surface profile computed by step-backwater will converge to normal depth at some point upstream for subcritical flow. Establishment of the upstream and downstream boundaries of the stream reach is required to define the limits of data collection and subsequent analysis. Calculations must begin sufficiently far downstream to assure accurate results at the structure site, and continued a sufficient distance upstream to accurately determine the impact of the structure on upstream water surface profiles (see Figure 8-7).

USACE *(27)* developed equations for determining upstream and downstream reach lengths as follows:

$$Ldn = 8000\ (HD^{0.8}/S) \qquad (8.19)$$

$$Lu = 10{,}000\ [(HD^{0.6})(HL^{0.5})]/S \qquad (8.20)$$

where: Ldn = downstream study length (along main channel), ft (for normal depth starting conditions)

Lu = estimated upstream study length (along main channel), ft (required for convergence of the modified profile to within 0.1 ft of the base profile)

HD = average hydraulic depth (1% chance event flow area divided by the top width), ft

S = average reach slope, ft/mi

HL = headloss ranging between 0.5 ft and 5 ft at the channel crossing structure for the 1% chance flood, ft

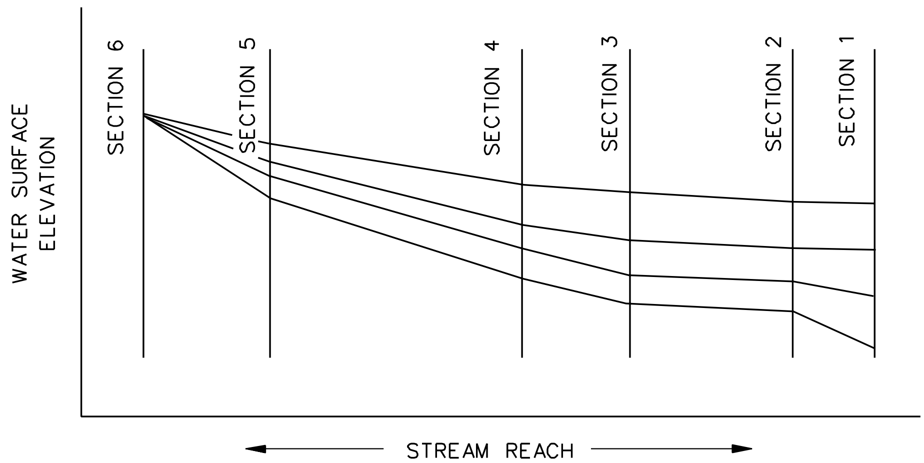
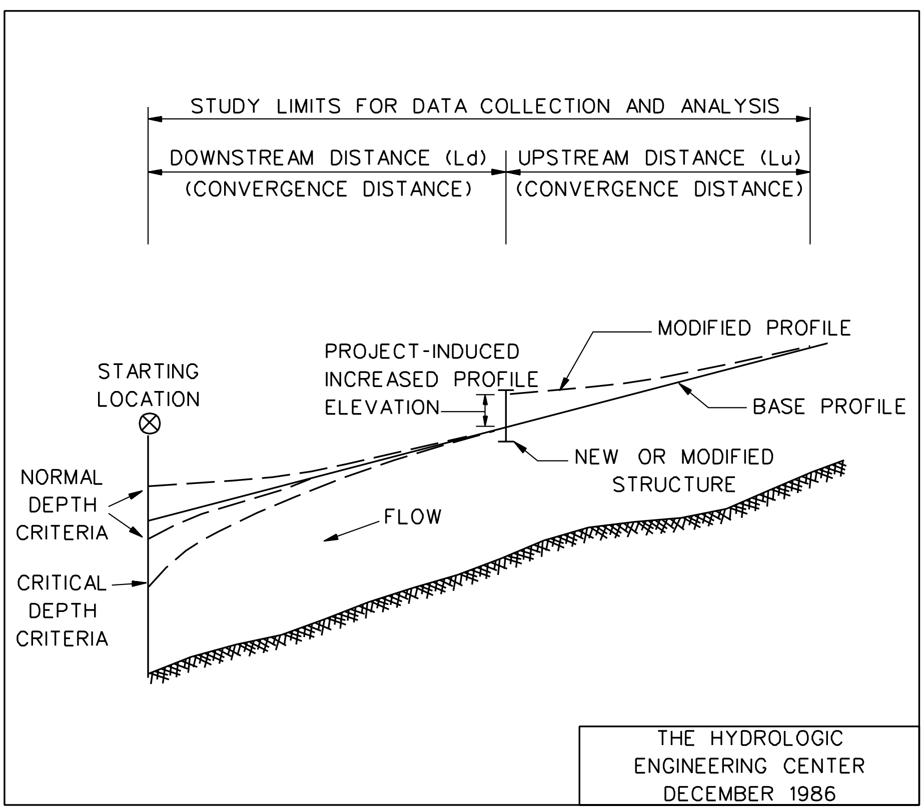


FIGURE 8-6 — Profile Convergence Pattern Backwater Computation



Source: Reference *(27)*.

FIGURE 8-7 — Profile Study Limits

References *(9)*, *(27)* are very valuable sources of additional guidance on the practical application of the step-backwater method to highway drainage problems involving open channels. These references contain more specific guidance on cross section determination, location and spacing and stream reach determination. Reference *(27)* investigates the accuracy and reliability of water surface profiles related to n-value determination and the survey or mapping technology used to determine the cross section coordinate geometry.

8.5.4.4 Computation Procedure

A sample procedure is taken from Reference *(31)*.

A convenient form for use in calculating water surface profiles is shown in Figure 8-8. In summary, Columns 2 and 4 through 12 are devoted to solving Manning's equation to obtain the energy loss due to friction; Columns 13 and 14 contain calculations for the velocity distribution across the section; Columns 15 through 17 contain the average kinetic energy; Column 18 contains calculations for "other losses" (expansion and contraction losses due to interchanges between kinetic potential energies as the water flows); and Column 19 contains the computed change in water surface elevation. Conservation of energy is accounted for by proceeding from section to section down the computation form.

Column 1 CROSS SECTION NO., is the cross section identification number. Miles upstream from the mouth are recommended.

Column 2 ASSUMED, is the assumed water surface elevation that must agree with the resulting, computed water surface elevation within $\pm$ 0.05 ft, or some allowable tolerance, for trial calculations to be successful.

Column 3 COMPUTED, is the rating curve value for the first section but, thereafter, is the value calculated by adding WS to the computed water surface elevation for the previous cross section.

Column 4 A, is the cross section area. If the section is complex and has been subdivided into several parts (e.g., left overbank, channel and right overbank), use one line of the form for each subsection and sum to get A_t, the total area of cross section.

Column 5 R, is the hydraulic radius. Use the same procedure as for Column 4 if section is complex, but do not sum subsection values.

Column 6 $R^{2/3}$, is 2/3 power of hydraulic radius.

Column 7 n, is Manning roughness coefficient.

Column 8 K, is conveyance and is defined as ($C_m AR^{2/3}/n$) where C_m is 1.486. If the cross section is complex, sum subsection K values to get K_t.

Column 9 $\overline{K}_t$, is average conveyance for the reach, and is calculated by $0.5(K_{td} + K_{tu})$ where subscripts D and U refer to downstream and upstream ends of the reach, respectively.

Cross Section No.	Water Surface Elevation		Area	Hydraulic Radius (R)	$R^{2/3}$	n	K	$\bar{K}_t$	1000 $\bar{S}_f$	L	h_f	K^3/A^2	α	V	$\alpha V^2/2g$	$\Delta(\alpha V^2/2g)$	h_o	Δ Water Surface Elevation
	Assumed	Computed																
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)

FIGURE 8-8 — Water Surface Profile Form

Column 10 $\overline{S}_f$, is the average slope through the reach determined by $(Q/\overline{K}_t)^2$.

Column 11 L, is the discharge-weighted or conveyance-weighted reach length.

Column 12 h_f, is energy loss due to friction through the reach and is calculated by $h_f = (Q/\overline{K}_t)^2 L = \overline{S}_f L$.

Column 13 $\Sigma(K^3/A^2)$, is part of the expression relating distributed flow velocity to an average value. If the section is complex, calculate one of these values for each subsection and sum all subsection values to get a total. If one subsection is used, Column 13 is not needed and Column 14 equals one.

Column 14 α, is the velocity distribution coefficient and is calculated by $\Sigma(K^3/A^2)/(K_t^3/A_t^2)$ where the numerator is the sum of values in Column 13 and the denominator is calculated from K_t and A_t.

Column 15 V, is the average velocity and is calculated by Q/A_t.

Column 16 $\alpha V^2/2g$, is the average velocity head corrected for flow distribution.

Column 17 $\Delta(\alpha V^2/2g)$, is the difference between velocity heads at the downstream and upstream sections. A positive value indicates velocity is increasing; therefore, use a contraction coefficient for "other losses." A negative value indicates the expansion coefficient should be used in calculating "other losses."

Column 18 h_o, is "other losses," and is calculated by multiplying either the expansion or contraction coefficient, K_m, times the absolute value of Column 17.

Column 19 ΔWS, is the change in water surface elevation from the previous cross section. It is the algebraic sum of Columns 12, 17 and 18.

8.5.5 Special Analysis Techniques

Open channel flow problems sometimes arise that require a more detailed analysis than a single-section analysis or the computation of a water surface profile using the Standard-Step Method or the Direct-Step Method. More detailed analysis techniques include two-dimensional analysis, water and sediment routing and unsteady flow analysis. Computer programs are available for the analysis techniques discussed in this Section.

8.5.5.1 Two-Dimensional Analysis

Two-dimensional (2-D) models simulate flow in two directions — longitudinal and transverse at a series of user-defined node points. Flow in the vertical direction is assumed to be negligible. These models can account for transverse flow due to lateral velocities and water surface gradients that cannot be accounted for with one-dimensional models. Examples of such conditions include skewed bridges, floodplain crossings with multiple openings, channel bifurcation, flow around channel bends and flow around islands.

A 2-D model should be considered for major projects with complex flow patterns that one-dimensional models cannot adequately analyze. Examples of situations where 2-D models should be considered are as follows:

- wide floodplains with multiple openings, particularly on skewed embankments;
- floodplains with significant variations in roughness or complex geometry such as ineffective flow areas, flow around islands or multiple channels;
- sites where more accurate flow patterns and velocities are needed to design better and cost-effective countermeasures such as riprap along embankments and/or abutments;
- tidally affected river crossings and crossings of tidal inlets, bays and estuaries; and
- high-risk or sensitive locations where losses and liability costs are high.

Two commonly used computer programs for 2-D modeling are RMA2 (USACE 2000) and FESWMS-2DH (FESWMS) *(16)*. Both RMA2 and FESWMS model steady and unsteady flow. FESWMS is recommended for highway crossings of rivers and floodplains because it supports both super and subcritical flow analysis and can analyze weirs (roadway overtopping), culverts and bridges. The Surface Water Modeling System (SMS) *(5)*, developed by the Engineering Computer Graphics Laboratory at Brigham Young University in cooperation with the USACE Waterways Experiment Station and the FHWA (Brigham Young University, 1995), can be used to develop the finite element mesh and associated boundary conditions necessary for RMA2 and FESWMS. The solution files from FESWMS or RMA2, which contain water surface elevation, velocity or other functional data at each node of the mesh, can be read into SMS to generate vector plots, color-shaded contour plots, time variant curve plots and dynamic animation sequences.

8.5.5.2 Water and Sediment Routing

The BRI-STARS (Bridge Stream Tube Model for Sediment Routing Alluvial River Simulation) Model (References *(20)*, *(21)*) was developed by the National Cooperative Highway Research Program and FHWA. The objective of the model is to study complicated sedimentation problems for which there is interaction between the flowing water-sediment mixture and the alluvial river channel boundaries. It is based on utilizing the stream tube method of calculation that allows the lateral and longitudinal variation of hydraulic conditions and sediment activity at various cross sections along the study reach. Both energy and momentum functions are used in the BRI-STARS model so the water surface profile can be computed through combinations of subcritical and supercritical flows without interruption. The stream tube concept is used for hydraulic computations in a semi-two-dimensional way. For a fixed-width channel, once the hydraulic parameters in each stream tube are computed, the scour or deposition in each stream tube determined by sediment routing will give the variation of channel geometry in the vertical direction. BRI-STARS can also be used for decisions on whether the channel adjustments occurring at a given cross section due to scouring/deposition should advance in the lateral or vertical directions. The basic tool for this decision-making component is the “Minimum Rate of Energy Dissipation Theory” developed by Yang and Song *(35)* and this theory’s special case “Minimum Stream Power Theory” used by Chang *(6)*.

The BRI-STARS model contains a rule-based, expert system program for classifying streams by size, bed and bank material stability, planform geometry and other hydrologic and morphological features. Due to the complexities of a single classification system that utilizes all parameters, no universally acceptable stream classification method presently exists. Consequently, this model does not contain a single methodology for classifying all streams. Instead, methodologies were first classified according to the channel sediment sizes they were derived for then, within each size group, one or more classification schemes have been included to cover a wider range of environments. The stream classification information can be used to assist in the selection of model parameters and algorithms (see Section 8.8).

Applications of BRI-STARS can be summarized as follows:

- fixed-bed model to compute water surface profiles for subcritical, supercritical or the combination of both flow conditions involving hydraulic jumps;
- movable-bed model to route water and sediment through alluvial channels;
- use of stream tubes to allow the model to compute the variation of hydraulic conditions and sediment activity in the longitudinal and lateral directions. The armoring option allows simulation of longer-term riverbed changes;
- the minimization procedure option to allow the model to simulate channel widening and narrowing processes;
- the local bridge scour option to allow the computation of pier and abutment scour;
- computation of flows through bridge openings with the selection of the WSPRO bridge hydraulics option;
- the study of flow diversion problems through the use of lateral inflow/outflow options;
- the study of aggregate mining can be conducted by simulating various mining alternatives (quantity and physical location);
- the study of dredging with the sediment outflow option without any water outflow; and
- the simulation of bank failures with known rates of bank regression with the option of lateral sediment inflow without water inflow.

8.5.5.3 Unsteady Flow Analysis

One-dimensional, unsteady flow can be analyzed with the HEC-RAS (References *(28)*, *(29)*, *(30)*) computer program. Some of the features of HEC-RAS are the network simulation of split flow and combined flow. The effect of storage areas can also be analyzed. This feature is useful when the effects of a stream channel and/or overbank floodwater storage areas are sufficient to allow a significant reduction in peak rates approaching a drainage structure or series of structures. This program can provide more realistic estimates of headwater produced at a series of closely spaced highway drainage structures. HEC-RAS allows the user to analyze lateral overflow into storage areas over a gated spillway, weir, levee, through a culvert or a pumped diversion. The user can apply several external and internal boundary conditions, including flow and stage hydrographs, gated and controlled spillways, bridges, culverts and levee systems. HEC-RAS can be an effective tool to analyze tidally affected river crossings and crossings of tidal inlets, bays and estuaries. UNET (Reference *(32)*) can also be used to analyze one-dimensional unsteady flow, and it has the same modeling capabilities as HEC-RAS.

Two-dimensional, unsteady flow can be analyzed with either FESWMS-2DH *(16)* or RMA2 *(33)* as discussed in Section 8.5.5.1.

8.6 DESIGN PROCEDURE

8.6.1 General

The design procedure for all types of channels has some common elements and some substantial differences. This Section will outline a process for assessing a natural stream channel and a more specific design procedure for roadside channels.

8.6.2 Stream Channels

The analysis of a stream channel in most cases is in conjunction with the design of a highway hydraulic structure such as a culvert or bridge. In general, the objective is to convey the water along or under the highway such that it will not cause damage to the highway, stream or adjacent property. An assessment of the existing channel is usually necessary to determine the potential for problems that might result from a proposed action. The detail of studies necessary should be commensurate with the risk associated with the action and with the environmental sensitivity of the stream and adjoining floodplain (see Section 8.7).

Although the following step-by-step procedure may not be appropriate for all possible applications, it does outline a process that will usually apply.

Step 1 Assemble Site Data and Project File

A. Data Collection (see Data Collection Chapter):

- Topographic, site and location maps.
- Roadway profile.
- Photographs.
- Field reviews.
- Design data at nearby structures.
- Gaging records.
- Historic flood data and local knowledge.

B. Studies by other agencies:

- Flood insurance studies.
- Floodplain studies.
- Watershed studies.

C. Environmental constraints:

- Floodplain encroachment.
- Floodway designation.

- Fish and wildlife habitat.
- Commitments in review documents.

D. Design criteria:

- See Section 8.3.

Step 2 Determine the Project Scope

A. Determine level of assessment:

- Stability of existing channel.
- Potential for damage.
- Sensitivity of the stream.

B. Determine type of hydraulic analysis:

- Qualitative assessment.
- Single-section analysis.
- Step-backwater analysis.
- Special analysis techniques.

C. Determine additional survey information:

- Extent of streambed profiles.
- Locations of cross sections.
- Elevations of flood-prone property.
- Details of existing structures.
- Properties of bed and bank materials.

Step 3 Evaluate Hydrologic Variables and Compute Discharges for Selected Frequencies (Consult Hydrology Chapter)

Step 4 Perform Hydraulic Analysis

A. Either single-section analysis (Section 8.5.3).

- Select representative cross section (Section 8.5.2).
- Select appropriate n values (Table 8-2).
- Compute stage-discharge relationship.

B. or Step-backwater analysis (Section 8.5.4).

C. or special analysis techniques (Section 8.5.5).

D. Calibrate with known highwater.

Step 5 Perform Stability Analysis

A. Geomorphic factors.
B. Hydraulic factors.
C. Stream response to change.

Step 6 Design Countermeasures

A. Criteria for selection:

- Erosion mechanism.
- Stream characteristics.
- Construction and maintenance requirements.
- Vandalism considerations.
- Cost.

B. Types of countermeasures:

- Meander migration countermeasures.
- Bank stabilization (see Bank Protection Chapter).
- Bend control countermeasures.
- Channel braiding countermeasures.
- Degradation countermeasures.
- Aggradation countermeasures.

C. For additional information:

- HEC 20 Stream Stability *(15)*.
- HDS No. 6 River Engineering for Highway Encroachments *(14)*.
- See Reference List.

Step 7 Documentation

- Prepare report and file with background information.
- See Documentation Chapter.

8.6.3 Roadside Channels

A roadside channel is defined as an open channel usually paralleling the highway embankment and within the limits of the highway right-of-way. It is normally trapezoidal or V-shaped in cross section and lined with grass or a special protective lining.

The primary function of roadside channels is to collect surface runoff from the highway and areas that drain to the right-of-way and convey the accumulated runoff to acceptable outlet points.

A secondary function of a roadside channel is to drain subsurface water from the base of the roadway to prevent saturation and loss of support for the pavement or to provide a positive outlet for subsurface drainage systems such as pipe underdrains.

The alignment, cross section and grade of roadside channels is usually constrained to a large extent by the geometric and safety standards applicable to the project. These channels should accommodate the design runoff to ensure the safety of motorists and to minimize future maintenance, damage to adjacent properties and adverse environmental or aesthetic effects.

8.6.3.1 Step-By-Step Procedure

Each project is unique, but the following six basic design steps are normally applicable:

Step 1 Establish a Roadside Plan

A. Collect available site data.

B. Obtain or prepare existing and proposed plan-profile layout including highway, culverts and bridges.

C. Determine and plot on the plan the locations of natural basin divides and roadside channel outlets. An example of a roadside channel plan/profile is shown in Figure 8-9.

D. Perform the layout of the proposed roadside channels to minimize diversion flow lengths.

Step 2 Obtain or Establish Cross Section Data

A. Provide channel depth adequate to drain the subbase and minimize freeze-thaw effects.

B. Choose channel side slopes based on geometric design criteria including safety, economics, soil, aesthetics and access.

C. Establish bottom width of trapezoidal channel.

D. Identify features that may restrict cross section design:

- right-of-way limits,
- trees or environmentally sensitive areas,
- utilities, and
- existing drainage facilities.

Step 3 Determine Initial Channel Grades

A. Plot initial grades on plan-profile layout. (Slopes in roadside ditch in cuts are usually controlled by highway grades).

B. Provide minimum grade of 0.3% to minimize ponding and sediment accumulation.

C. Consider influence of type of lining on grade.

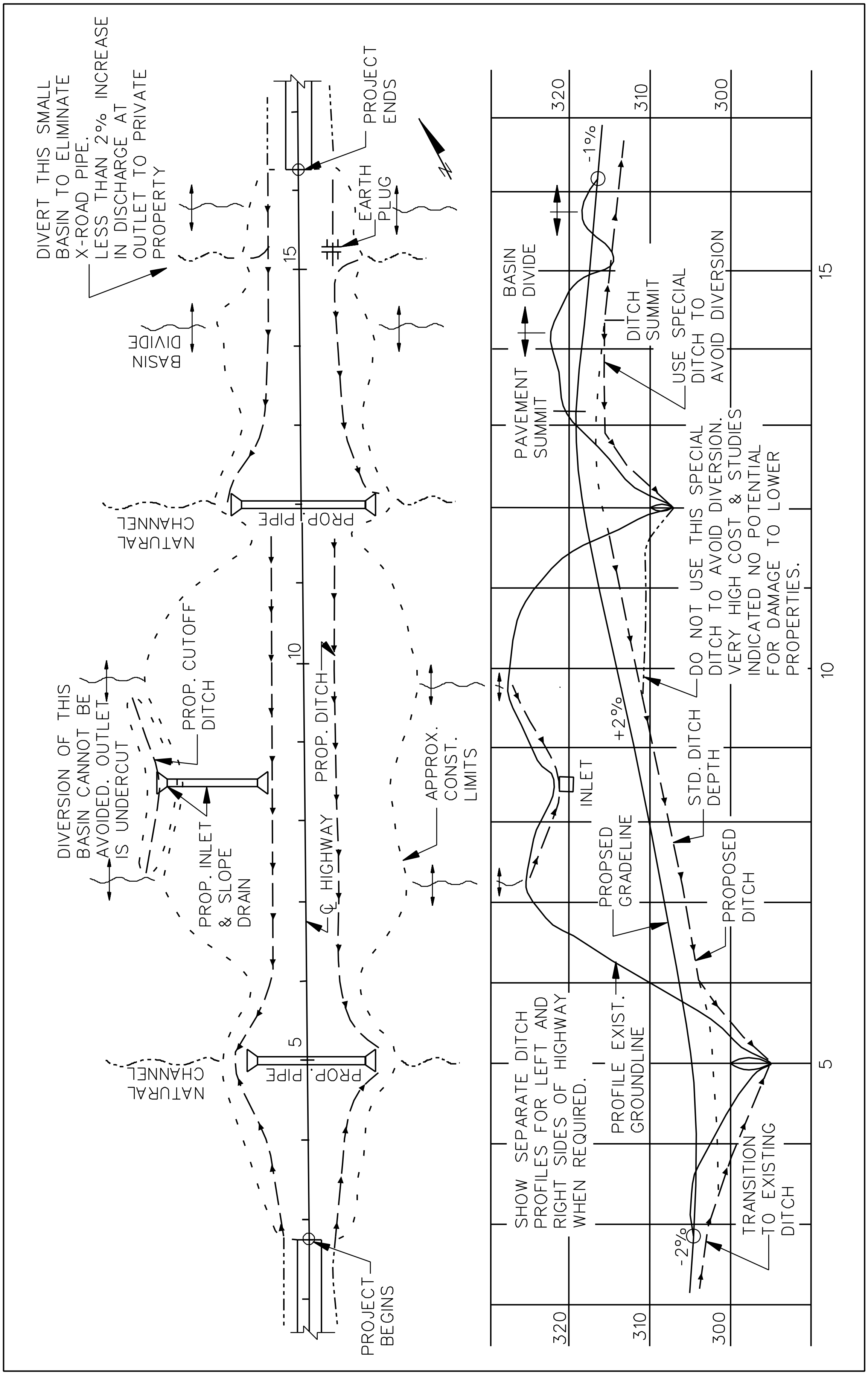


FIGURE 8-9 — Sample Roadside Channel

D. Where possible, avoid features that may influence or restrict grade (e.g., utility locations).

Step 4 Check Flow Capacities and Adjust as Necessary

A. Compute the design discharge at the downstream end of a channel segment (see Hydrology Chapter).

B. Set preliminary values of channel size, roughness coefficient and slope.

C. Determine maximum allowable depth of channel including freeboard.

D. Check flow capacity using Manning's equation and single-section analysis.

E. If capacity is inadequate, possible adjustments are as follows:

- increase bottom width,
- make channel side slopes flatter,
- make channel slope steeper,
- provide smoother channel lining, and
- install drop inlets and a parallel storm drain pipe beneath the channel to supplement channel capacity.

F. Provide smooth transitions at changes in channel cross sections.

G. Provide extra channel storage where needed to replace floodplain storage and/or to reduce peak discharge.

Step 5 Determine Channel Lining/Protection Needed (HEC 15) *(11)*

A. Select a lining and determine the permissible shear stress τ_p in lb/ft^2 from Table 8-3 and/or Table 8-4.

B. Estimate the flow depth and choose an initial Manning's n value from Table 8-5 or from Figures 8-10 through 8-15.

C. Calculate normal flow depth, y_o (ft), at design discharge using Manning's equation and compare with the estimated depth. If they do not agree, repeat Steps 5B and 5C.

D. Compute maximum shear stress at normal depth as:

τ_d (lb/ft^2) = 62.4 $y_o S$, where S = channel slope, ft/ft

TABLE 8-3 — Classification of Vegetal Covers as to Degrees of Retardancy

Retardance	Cover	Condition
A	Weeping lovegrass Yellow bluestem Ischaemum	Excellent stand, tall (average 30 in) Excellent stand, tall (average 36 in)
B	Kudzu Bermuda grass Native grass mixture: little bluestem, bluestem, blue gamma other short- and long-stem Midwest grasses Weeping lovegrass Lasperdeza sericea Alfalfa Weeping lovegrass Kudzu Blue gamma	Very dense growth, uncut Good stand, tall (average 12 in) Good stand, unmowed Good stand, tall (average 24 in) Good stand, not woody, tall (average 19 in) Good stand, uncut (average 11 in) Good stand, unmowed (average 13 in) Dense growth, uncut Good stand, uncut (average 13 in)
C	Crabgrass Bermuda grass Common lesperdeza Grass-legume mixture: summer (orchard grass redtop, Italian ryegrass and common lespedeza) Centipedegrass Kentucky bluegrass	Fair stand, uncut (10 in – 48 in) Good stand, mowed (average 6 in) Good stand, uncut (average 11 in) Good stand, uncut (6 in – 8 in) Very dense cover (average 6 in) Good stand, headed (6 in – 12 in)
D	Bermuda grass Common lespedeza Buffalo grass Grass-legume mixture: fall, spring (orchard grass redtop, Italian ryegrass and common lesperdeza) Lespedeza serices	Good stand, cut to 2½ in Excellent stand, uncut (average 4½ in) Good stand, uncut (3 in – 6 in) Good stand, uncut (4 in – 5 in) After cutting to 2 in (very good before cutting)
E	Bermuda grass Bermuda grass	Good stand, cut to 1½ in Burned stubble

Note: Covers classified have been tested in experimental channel. Covers were green and generally uniform. Source of table is HEC 15 *(11)*.

TABLE 8-4 — Summary of Permissible Shear Stress for Various Protection Measures

Protective Cover	Underlying Soil	τ_p lb/ft^2
Class A Vegetation	Erosion Resistant or Erodible	3.70
Class B Vegetation	Erosion Resistant or Erodible	2.10
Class C Vegetation	Erosion Resistant or Erodible	1.00
Class D Vegetation	Erosion Resistant or Erodible	0.60
Class E Vegetation	Erosion Resistant or Erodible	0.35
Woven Paper		0.15
Jute Net		0.45
Single Fiberglass		0.60
Double Fiberglass		0.85
Straw w/Net		1.45
Curved Wood Mat		1.55
Synthetic Mat		2.00
Plain Grass, Good Cover	Clay	N/A
Plain Grass, Average Cover	Clay	N/A
Plain Grass, Poor Cover	Clay	N/A
Grass, Reinforced with Nylon	Clay	N/A
Dycel with Grass	Clay	N/A
Petraflex with Grass	Clay	N/A
Armorflex with Grass	Clay	N/A
Dymex with Grass	Clay	N/A
Grasscrete	Clay	N/A
Gravel		
D_{50} = 1 in		0.40
D_{50} = 2 in		0.80
Rock		
D_{50} = 6 in		2.50
D_{50} = 12 in		5.00
6 in Gabions	Type I	35.00
4 in Geoweb	Type I	10.00
Soil Cement (8% cement)	Type I	>45.00
Dycel w/o Grass	Type I	>7.00
Petraflex w/o Grass	Type I	>32.00
Armorflex w/o Grass	Type I	12.00 – 20.00
Enkamat w/3 in in Asphalt	Type I	13.00 – 16.00
Erikamat w/1 in in Asphalt	Type I	<5.00
Armorflex Class 30, longitudinal and lateral cables, no grass	Type I	>34.00
Dycell 100, longitudinal cables, cells filled with mortar	Type I	<12.00
Concrete construction blocks, granular filter underlayer	Type I	>20.00
Wedge-shaped blocks with drainage slot	Type I	>25.00
Type I soil is a silty clay to silty sand (SC-SM) with AASHTO classification A-4(0).		

Source: Reference *(13)*.

TABLE 8-5 — Manning's Roughness Coefficients and Roughness Element Height, k_s

Lining Category	Lining Type	k_s(ft)	n - value Depth Ranges 0 – 0.5 ft	0.5 – 2.0 ft	>2.0 ft
Rigid	Concrete		0.015	0.013	0.013
	Grouted Riprap		0.040	0.030	0.028
	Stone Masonry		0.042	0.032	0.030
	Soil Cement		0.025	0.022	0.020
	Asphalt		0.018	0.016	0.016
Unlined	Bare Soil		0.023	0.020	0.020
	Rock Cut		0.045	0.035	0.025
Temporary*	Woven Paper Net	0.003	0.016	0.015	0.015
	Jute Net	0.039	0.028	0.022	0.019
	Fiberglass Roving	0.036	0.028	0.022	0.019
	Straw with Net	0.121	0.065	0.033	0.025
	Curled Wood Mat	0.112	0.066	0.035	0.028
	Synthetic Mat	0.066	0.036	0.025	0.021
Gravel Riprap	1 in D_{50}	0.082	0.044	0.033	0.030
	2 in D_{50}	0.164	0.066	0.041	0.034
Rock Riprap	6 in D_{50}	0.492	0.104	0.069	0.035
	12 in D_{50}	0.984	—	0.078	0.040

Note: Values listed are representative values for the respective depth ranges. Manning's roughness coefficients, n, vary with the flow depth. For riprap, $k_s = D_{50}$.

*Some "temporary" linings become permanent when buried.

Source: HEC 15 *(11)*.

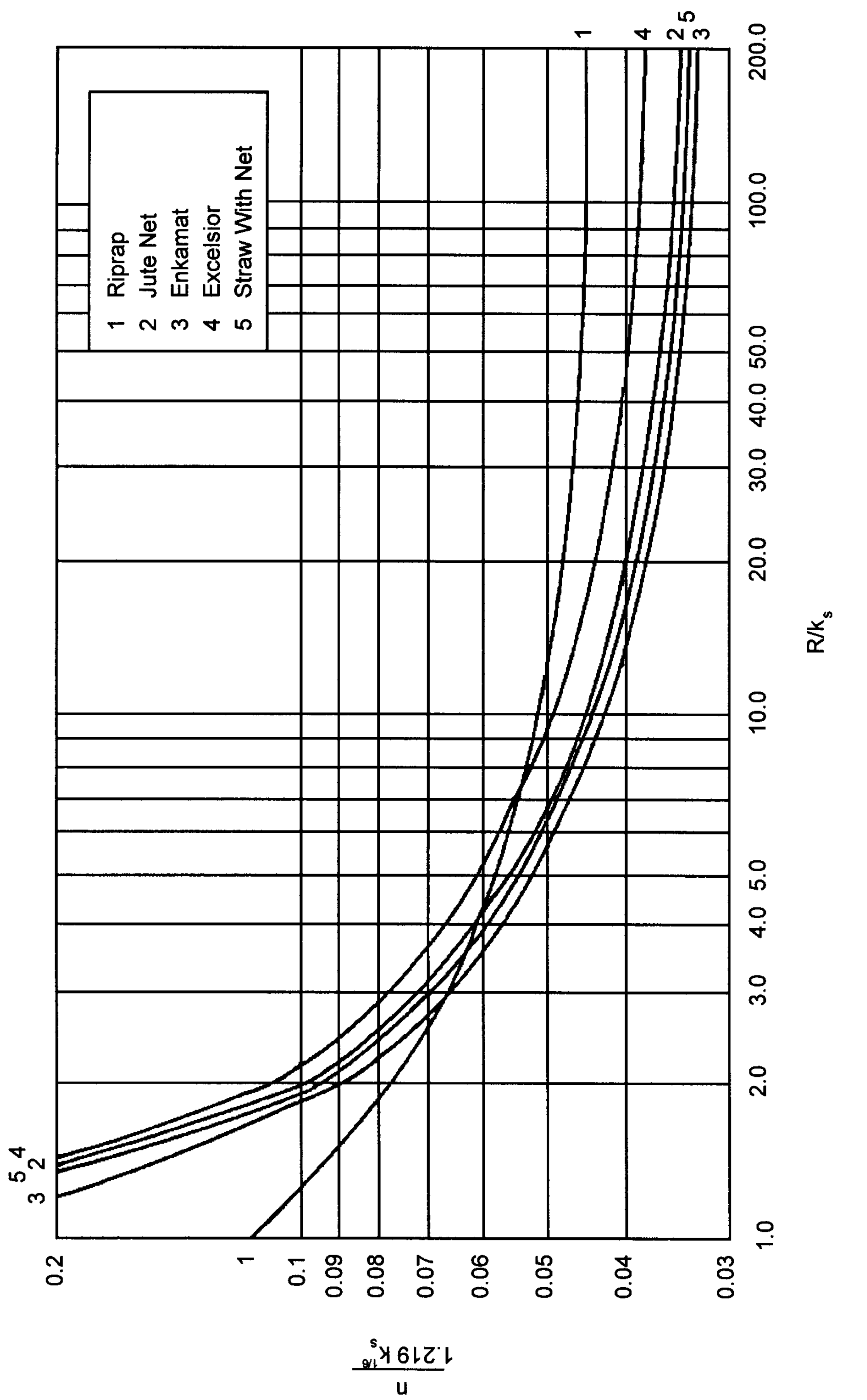


FIGURE 8-10—Manning's n Versus Relative Roughness For Selected Lining Types (HEC 15 *(11)*)

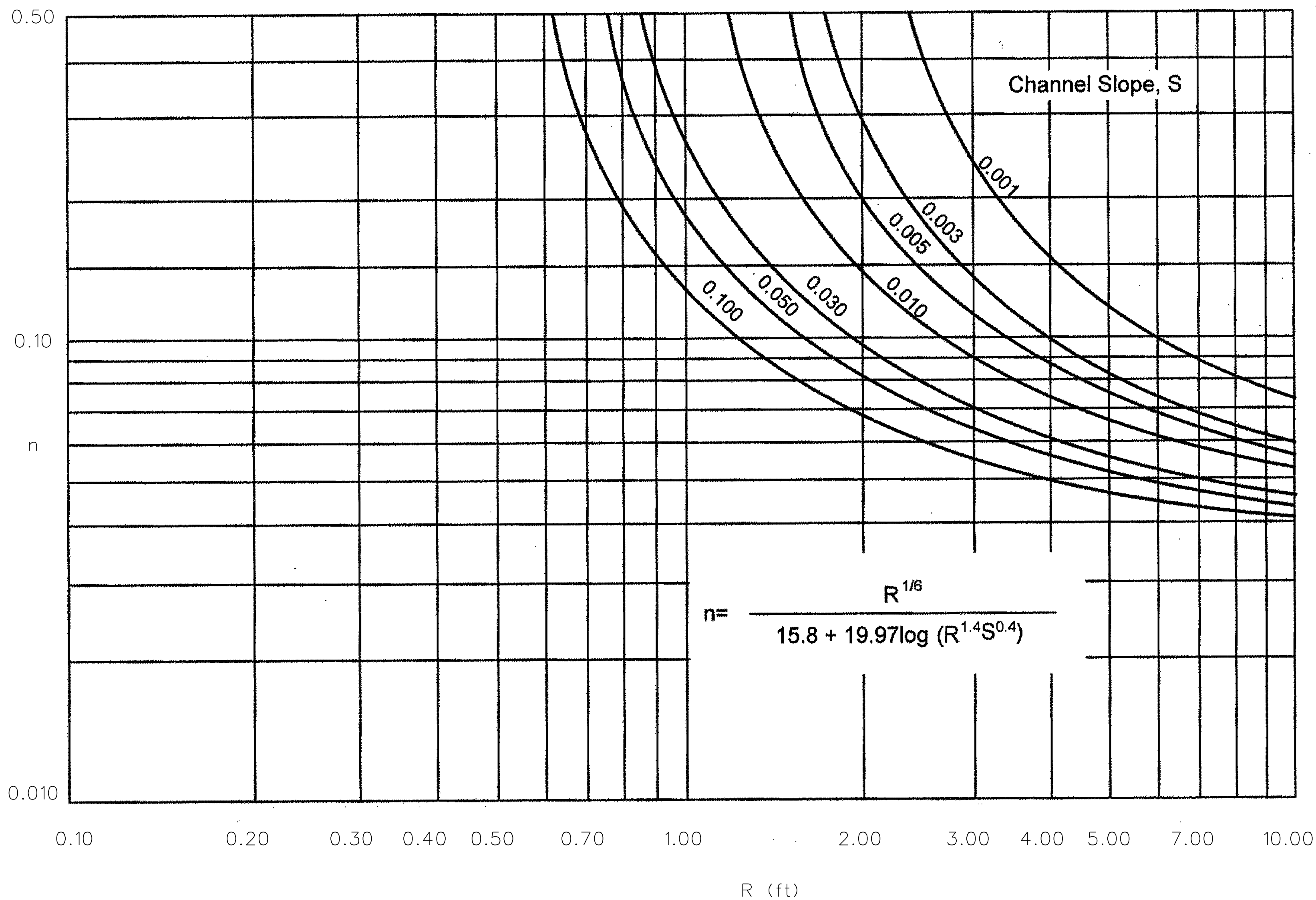


FIGURE 8-11 — Manning's n Versus Hydraulic Radius, R, For Class A Vegetation (HEC 15 *(11)*)

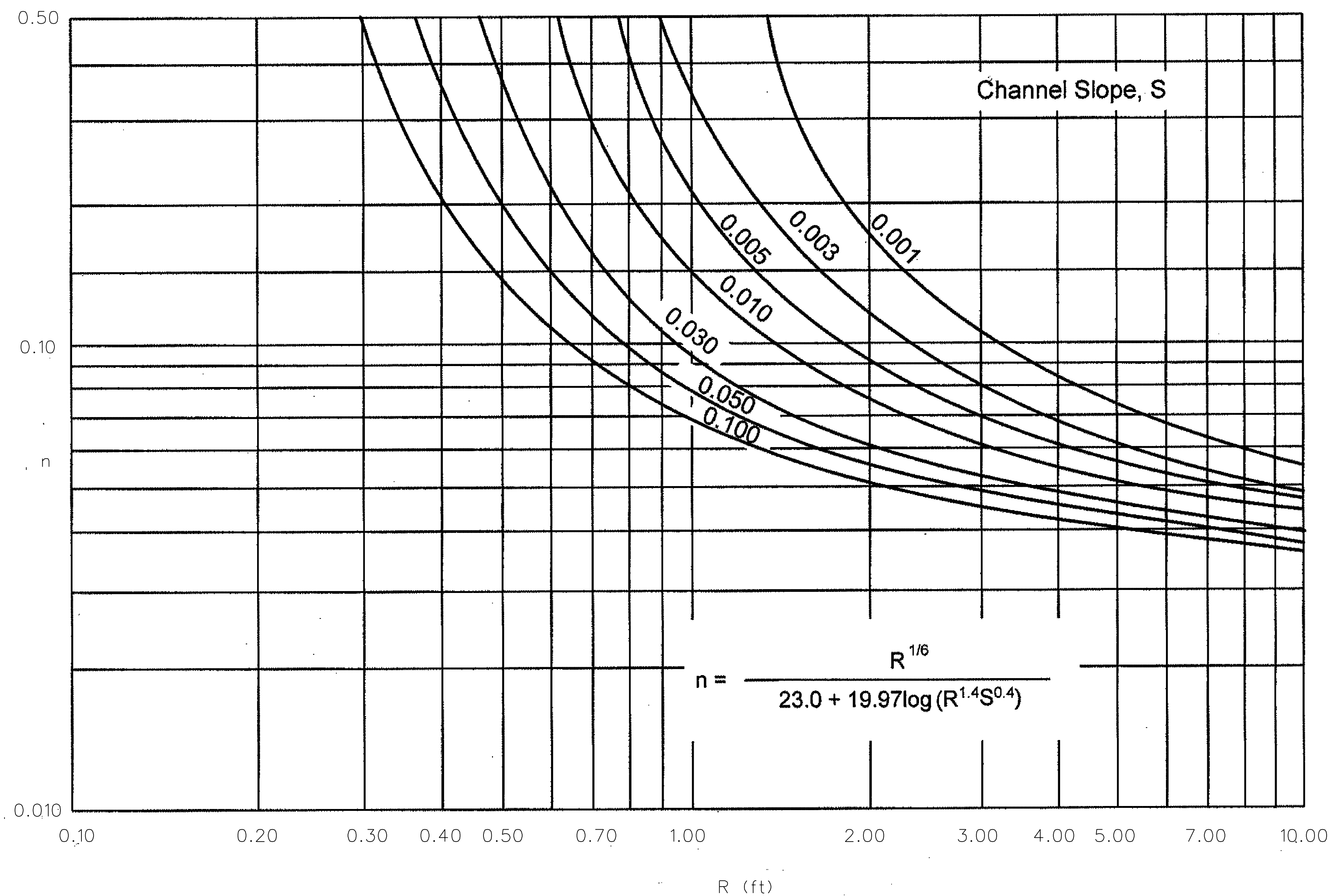


FIGURE 8-12 — Manning's n Versus Hydraulic Radius, R, For Class B Vegetation (HEC 15 *(11)*)

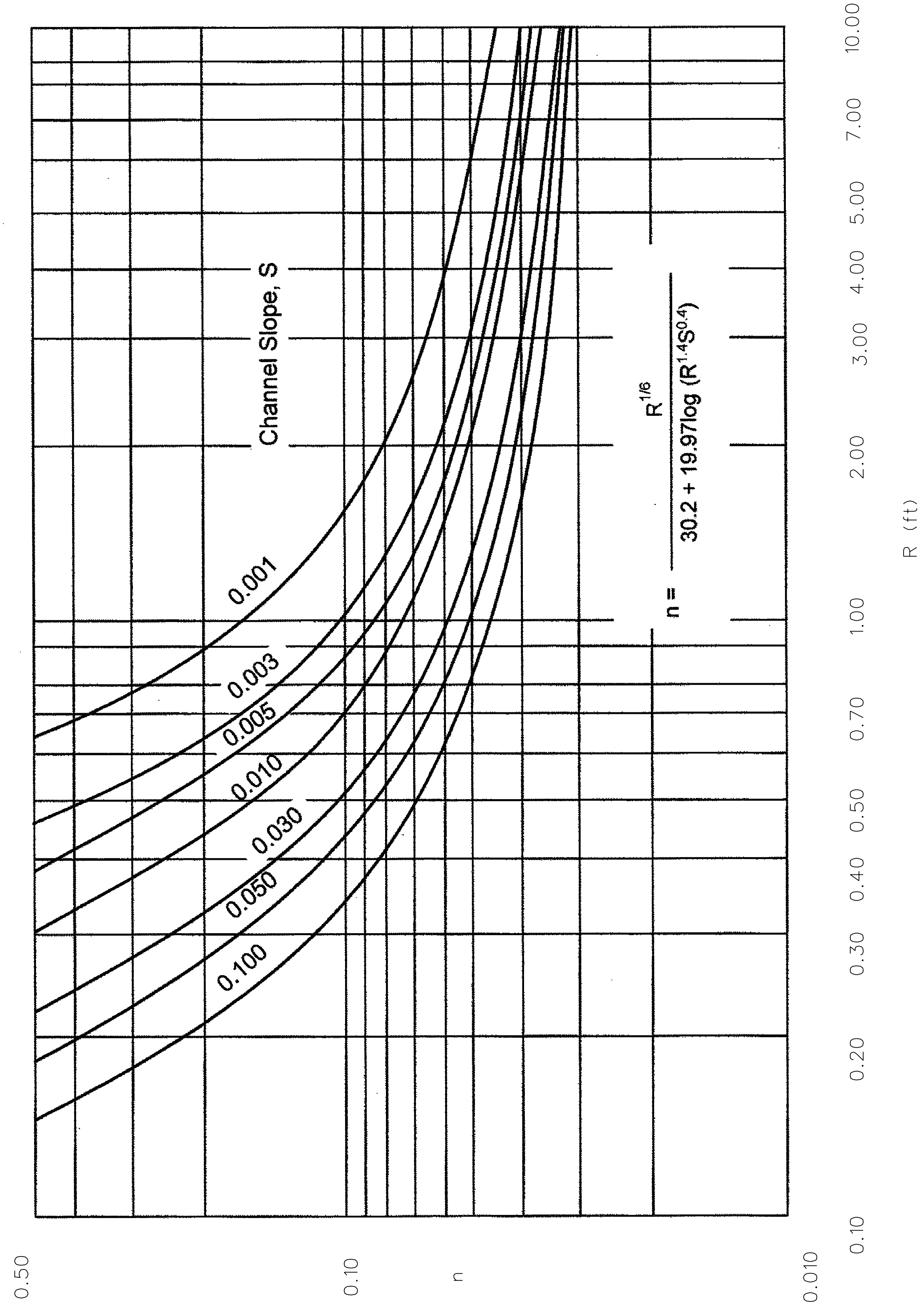


FIGURE 8-13 — Manning's n Versus Hydraulic Radius, R, For Class C Vegetation (HEC 15 *(11)*)

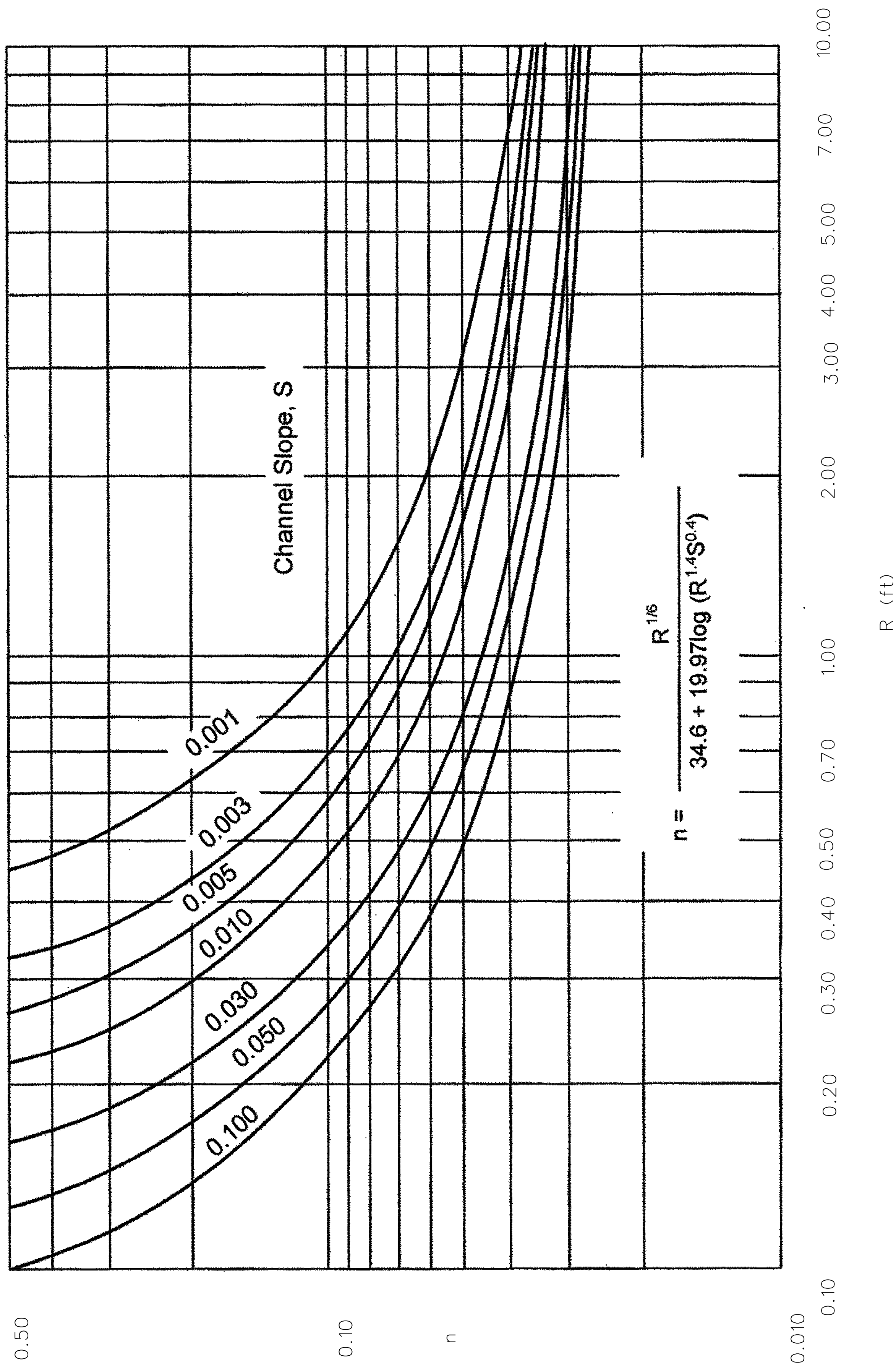


FIGURE 8-14 — Manning's n Versus Hydraulic Radius, R, For Class D Vegetation (HEC 15 *(11)*)

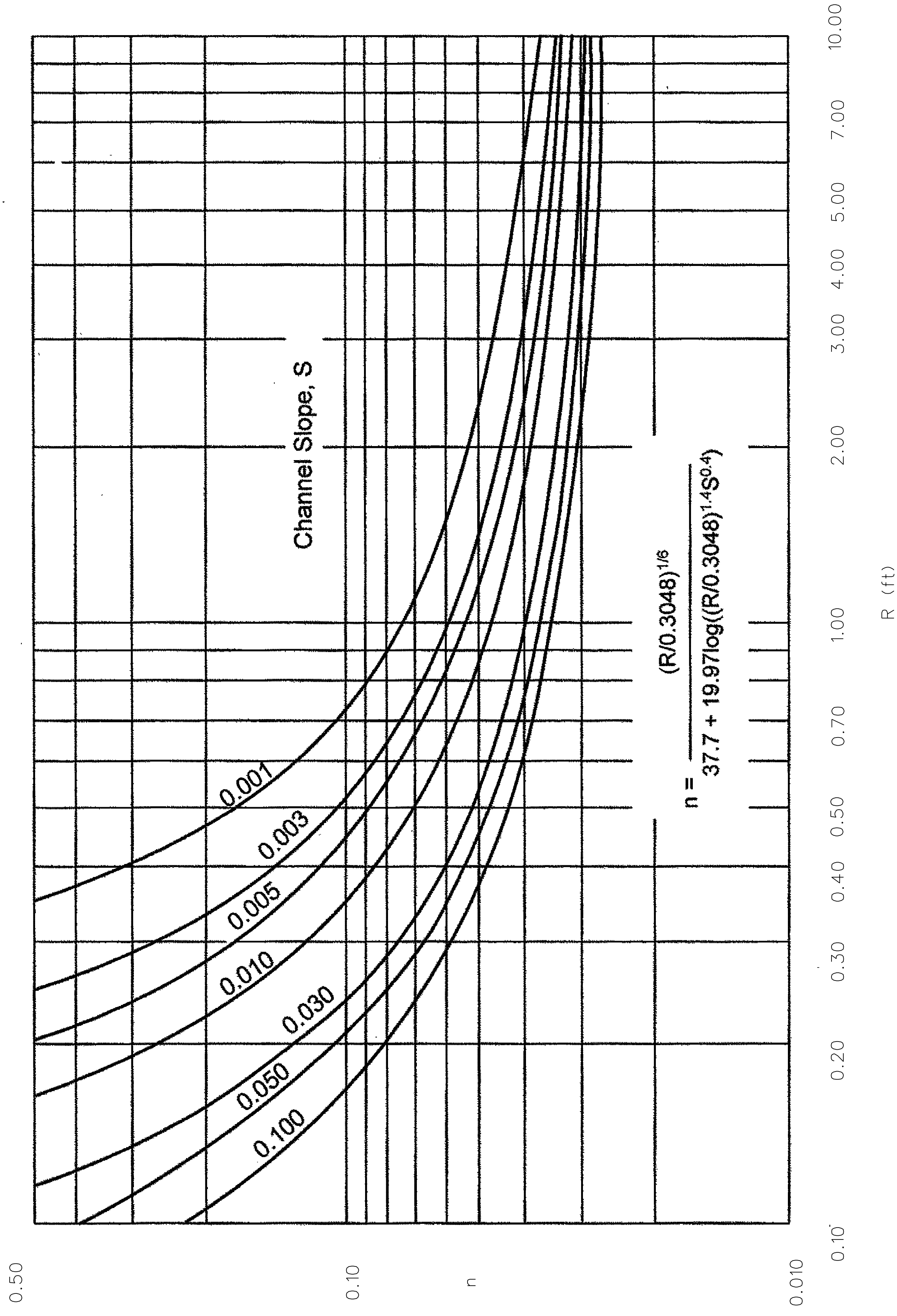


FIGURE 8-15 — Manning's n Versus Hydraulic Radius, R, For Class E Vegetation (HEC 15 *(11)*)

E. If $\tau_d < \tau_p$, then lining is acceptable. Otherwise consider the following options:

- choose a more resistant lining;
- use concrete, gabions or other more rigid lining either as full lining or composite;
- decrease channel slope;
- decrease slope in combination with drop structures; and/or
- increase channel width and/or flatten side slopes.

Step 6 <u>Analyze Outlet Points and Downstream Effects</u>

A. Identify any adverse impacts (e.g., increased flooding or erosion to downstream properties) that may result from one of the following at the channel outlet:

- increase or decrease in discharge,
- increase in velocity of flow,
- concentration of sheet flow,
- change in outlet water quality, or
- diversion of flow from another watershed.

B. Mitigate any adverse impacts identified in Step 6A. Possibilities include:

- enlarge outlet channel and/or install control structures to provide detention of increased runoff in channel,
- install velocity-control structures (energy dissipators),
- increase capacity and/or improve lining of downstream channel,
- install sedimentation/infiltration basins,
- install sophisticated weirs or other outlet devices to redistribute concentrated channel flow, and
- eliminate diversions that result in downstream damage and that cannot be mitigated in a less expensive fashion.

8.6.3.2 Design Considerations

To obtain the optimum roadside channel system design, it may be necessary to make several trials of the previous procedure before a final design is achieved.

More details on channel lining design may be found in HEC 15 *(11)* including consideration of channel bends, steep slopes and composite linings. The riprap design procedures covered in HEC 15 are for channels having a design discharge of 50 ft^3/s or less. When the design discharge exceeds 50 ft^3/s, the design procedure presented in the Bank Protection Chapter should be followed.

8.7 STREAM MORPHOLOGY

8.7.1 Introduction

The form assumed by a natural stream, which includes its cross-sectional shape and its planform, is a function of many variables for which cause-and-effect relationships are difficult to establish. The stream may be graded or in equilibrium with respect to long time periods, which means that on average it discharges the same amount of sediment that it receives, although there may be short-term adjustments in its bedforms in response to flood flows. In contrast, the stream reach of interest may be aggrading or degrading as a result of deposition or scour in the reach, respectively. The planform of the stream may be straight, braided or meandering. These complexities of stream morphology can be assessed by inspecting aerial photographs and topographic maps for changes in slope, width, depth, meander form and bank erosion with time.

A qualitative assessment of the river response to proposed highway facilities is possible through a thorough knowledge of river mechanics and accumulation of engineering experience.

Equilibrium sediment load calculations can be made by a variety of techniques and compared from reach to reach to detect an imbalance in sediment inflow and outflow and thus identify an aggradation/degradation problem. The BRI-STARS model (see Section 8.5.5) is recommended as a tool to quantify the expected scour and/or sedimentation of potential problem locations. References *(14)*, *(21)* should be consulted to evaluate the problem and propose mitigation measures and the proposed methodology should be approved by the Department Hydraulics Engineer.

The natural stream channel will assume a geomorphological form that will be compatible with the sediment load and discharge history, which it has experienced over time. To the extent that a highway structure disturbs this delicate balance by encroaching on the natural channel, the consequences of flooding, erosion and deposition can be significant and widespread. The hydraulic analysis of a proposed highway structure should include a consideration of the extent of these consequences.

8.7.2 Levels of Assessment

The analysis and design of a stream channel will usually require an assessment of the existing channel and the potential for problems as a result of the proposed action. The detail of studies necessary should be commensurate with the risk associated with the action and with the environmental sensitivity of the stream. Observation is the best means of identifying potential locations for channel bank erosion and subsequent channel stabilization. Analytical methods for the evaluation of channel stability can be classified as either hydraulic or geomorphic, and it is important to recognize that these analytical tools should only be used to substantiate the erosion potential indicated through observation. A brief description of the three levels of assessment are as follows.

8.7.2.1 Level 1

Qualitative assessment involving the application of geomorphic concepts to identify potential problems and alternative solutions. Data needed may include historic information, current site conditions, aerial photographs, old maps and survey notes, bridge design files, maintenance records and interviews with long-time residents.

8.7.2.2 Level 2

Quantitative analysis combined with a more detailed qualitative assessment of geomorphic factors. Generally includes water surface profile and scour calculations. This level of analysis will be adequate for most locations if the problems are resolved and relationships between different factors affecting stability are adequately explained. Data needed will include Level 1 data in addition to the information needed to establish the hydrology and hydraulics of the stream.

8.7.2.3 Level 3

Complex quantitative analysis based on detailed mathematical modeling and possibly physical hydraulic modeling. Necessary only for high-risk locations, extraordinarily complex problems and possibly after-the-fact analysis where losses and liability costs are high. This level of analysis may require professionals experienced with mathematical modeling techniques for sediment routing (see Section 8.5.5) and/or physical modeling. Data needed will require Level 1 and 2 data and field data on bed load and suspended load transport rates and properties of bed and bank materials (e.g., size, shape, gradation, fall velocity, cohesion, density, angle of repose).

8.7.3 Factors That Affect Stream Stability

Factors that affect stream stability and, potentially, bridge and highway stability at stream crossings, can be classified as geomorphic factors and hydraulic factors.

Geomorphic Factors

These include:

- stream size,
- valley setting,
- natural levees,
- sinuosity,
- width variability,
- bar development,
- flow variability,
- floodplains,
- apparent incision,
- channel boundaries,
- degree of braiding, and
- degree of anabranching.

Figure 8-16 depicts examples of the various geomorphic factors.

Hydraulic Factors

These include:

- magnitude, frequency and duration of floods;

- bed configuration;

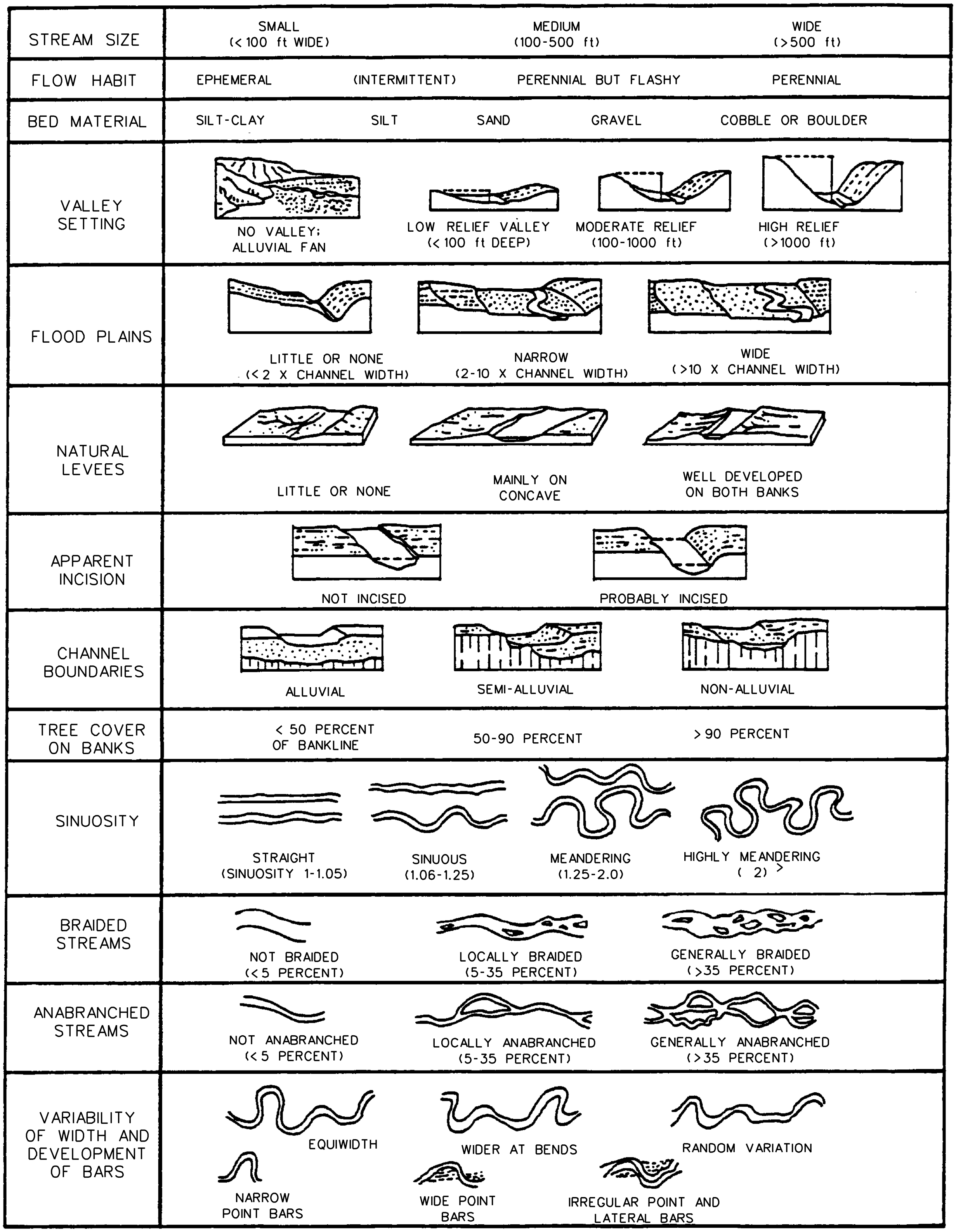


FIGURE 8-16 — Geomorphic Factors That Affect Stream Stability

Source: Adapted From Reference *(4)*.

- resistance to flow; and
- water surface profiles.

Figure 8-17 depicts the changes in channel classification and relative stability as related to hydraulic factors.

Rapid and unexpected changes may occur in streams in response to man's activities in the watershed such as alteration of vegetative cover. Changes in perviousness can alter the hydrology of a stream, sediment yield and channel geometry. Channelization, stream channel straightening, stream levees and dikes, bridges and culverts, reservoirs and changes in land use can have major effects on stream flow, sediment transport and channel geometry and location. Knowing that man's activities can influence stream stability can help the designer anticipate some of the problems that can occur.

Natural disturbances (e.g., floods, drought, earthquakes, landslides, volcanoes, forest fires) can also cause large changes in sediment load and thus major changes in the stream channel. Although difficult to plan for such disturbances, it is important to recognize that, when natural disturbances do occur, it is likely that changes will also occur to the stream channel.

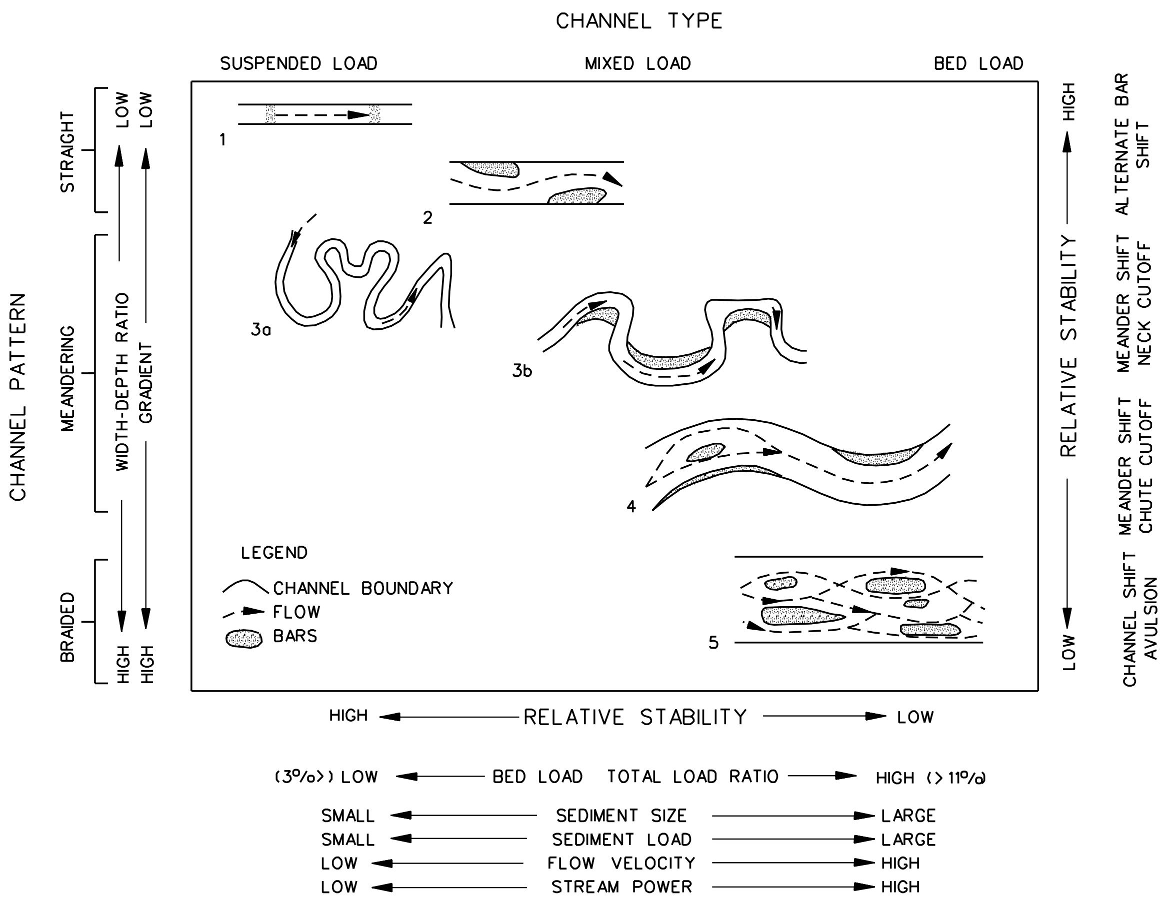


FIGURE 8-17 — Channel Classification and Relative Stability As Hydraulic Factors Are Varied

Source: After Reference *(25)*.

8.7.4 Stream Response To Change

The major complicating factors in river mechanics are 1) the large number of interrelated variables that can simultaneously respond to natural or imposed changes in a stream system; and 2) the continual evolution of stream channel patterns, channel geometry, bars and forms of bed roughness with changing water and sediment discharge. To better understand the responses of a stream to the actions of man and nature, a few simple hydraulic and geomorphic concepts are presented herein.

The dependence of stream form on slope, which may be imposed independently of other stream characteristics, is illustrated schematically in Figure 8-18.

Any natural or artificial change that alters channel slope can result in modifications to the existing stream pattern. For example, a cutoff of a meander loop decreases channel sinuosity and increases channel slope. Referring to Figure 8-18, this shift in the plotting position to the right could result in a shift from a relatively tranquil, meandering pattern toward a braided pattern that varies rapidly with time, has high velocities, is subdivided by sandbars and carries relatively large quantities of sediment. Conversely, it is possible that a slight decrease in slope could change an unstable braided stream into a meandering one.

The different channel dimensions, shapes and patterns associated with different quantities of discharge and amounts of sediment load indicate that, as these independent variables change, major adjustments of channel morphology can be anticipated. Further, a change in hydrology may cause changes in stream sinuosity, meander wave length, and channel width and depth. A long period of channel instability with considerable bank erosion and lateral shifting of the channel may be required for the stream to compensate for the hydrologic change.

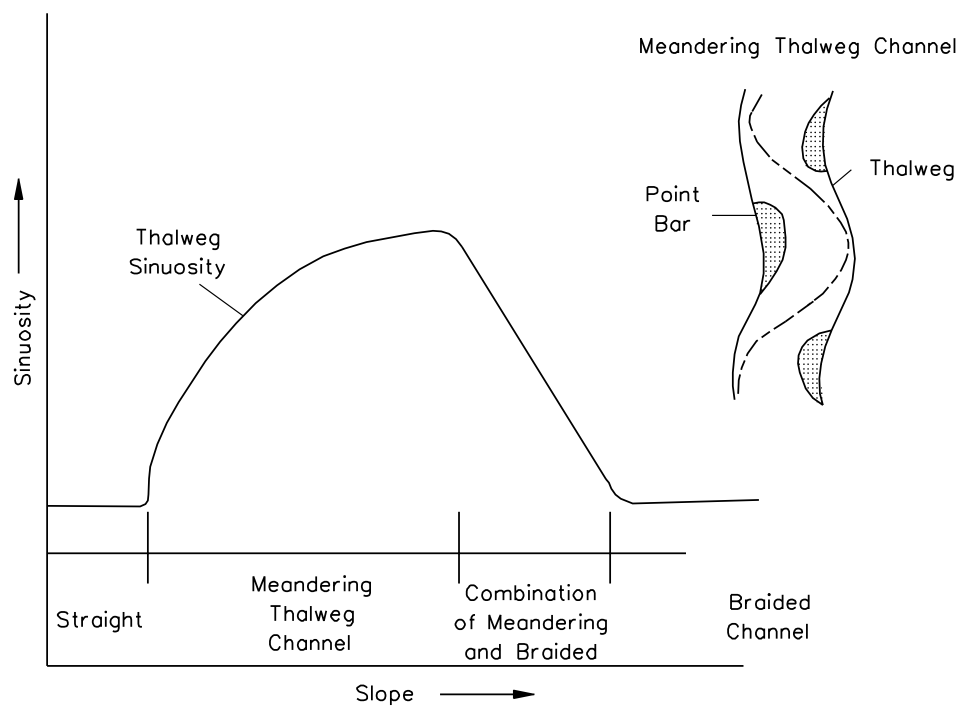


FIGURE 8-18 — Sinuosity Versus Slope with Constant Discharge

Source: After HDS No. 6 *(14)*.

Figure 8-19 illustrates the dependence of river form on channel slope and discharge, showing when $SQ^{0.25} \leq 0.00070$ in a sandbed channel, the stream will meander. Similarly, when $SQ^{0.25} \geq 0.0041$, the stream is braided.

In these equations, S is the channel slope in feet per foot, and Q is the mean discharge in cubic feet per second. Between these values of $SQ^{0.25}$ is the transitional range.

Many US rivers plot in this zone between the limiting curves defining meandering and braided streams. If a stream is meandering but its discharge and slope border on a boundary of the transitional zone, a relatively small increase in channel slope may cause it to change, in time, to a transitional or braided stream.

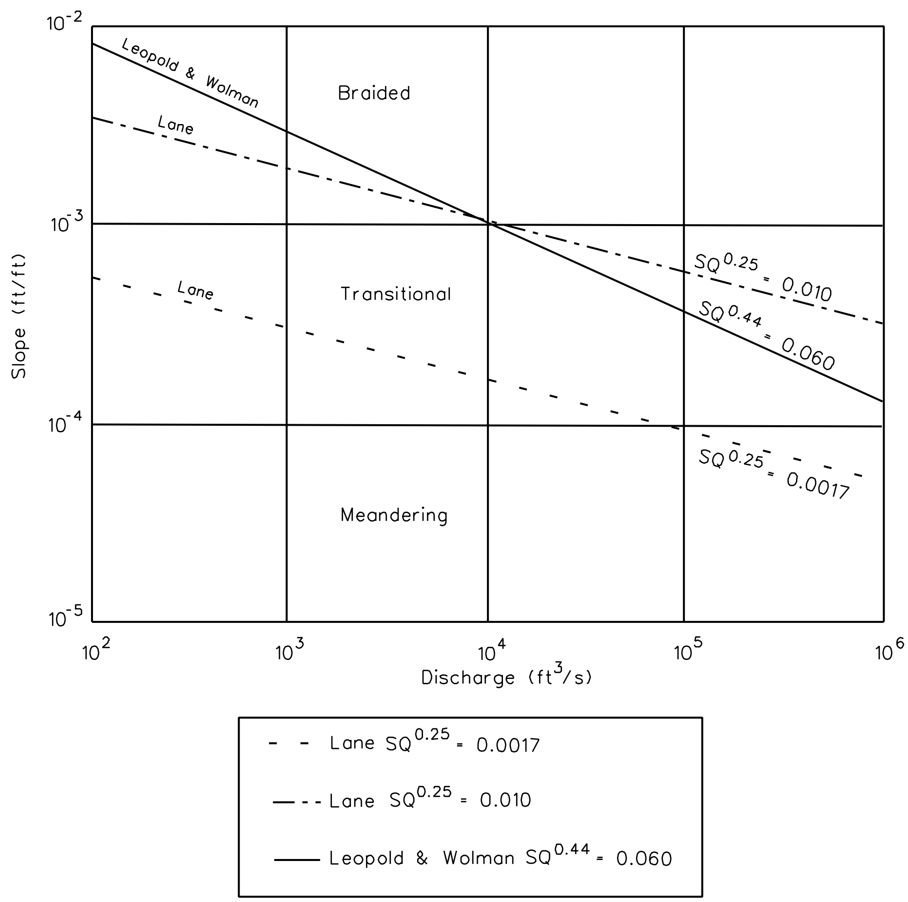


FIGURE 8-19 — Slope-Discharge For Braiding Or Meandering Bed Streams

Source: After Reference *(19)*.

8.7.5 <u>Countermeasures</u>

A countermeasure is defined as a measure incorporated into a highway crossing of a stream to control, inhibit, change, delay or minimize stream and bridge-stability problems. They may be installed at the time of highway construction or retrofitted to resolve stability problems at existing crossings.

Retrofitting is good economics and good engineering practice in many locations because the magnitude, location and nature of potential stability problems are not always discernible at the design stage and, indeed, may take a period of several years to develop.

The selection of an appropriate countermeasure for a specific bank erosion problem is dependent on factors such as the erosion mechanism, stream characteristics, construction and maintenance requirements, potential for vandalism and costs.

Below is a brief discussion of possible countermeasures for some common river-stability problems.

Note: The reader is encouraged to consult with the references listed at the end of this Chapter for detailed information on the design and construction of the countermeasures.

8.7.5.1 Meander Migration

The best countermeasure against meander migration is a crossing location on a relatively straight reach of stream between bends. Other countermeasures include the protection of an existing bank line, the establishment of a new flow line or alignment and the control and constriction of channel flow. Countermeasures identified for bank stabilization and bend control are bank revetments, spurs, retardance structures, longitudinal dikes, vane dikes, bulkheads and channel relocations. Measures may be used individually or a combination of two or more measures may be used to combat meander migration at a site (HDS 6 *(14)*, HEC 20 *(15)*).

8.7.5.2 Channel Braiding

Countermeasures used at braided streams are usually intended to confine the multiple channels to one channel. This tends to increase sediment transport capacity in the principal channel and encourage deposition in secondary channels.

The measures usually consist of dikes constructed from the limits of the multiple channels to the channel over which the bridge is constructed. Spur dikes at bridge ends used in combination with revetment on highway fill slopes, riprap on highway fill slopes only and spurs arranged in the stream channels to constrict flow to one channel have also been used successfully.

8.7.5.3 Degradation

Degradation in streams can cause the loss of bridge piers in stream channels and piers and abutments in caving banks. A check dam, which is a low dam or weir constructed across a channel, is one of the most successful techniques for halting degradation on small to medium streams.

Longitudinal stone dikes placed at the toe of channel banks can be effective countermeasures for bank caving in degrading streams. Precautions to prevent outflanking (e.g., tiebacks to the banks) may be necessary where installations are limited to the vicinity of the highway stream crossing. In general, channel lining alone is not a successful countermeasure against degradation problems (HEC 20 *(15)*).

8.7.5.4 Aggradation

Current measures in use to alleviate aggradation problems at highways include channelization, bridge modification, continued maintenance or combinations of these.

Channelization may include excavating and cleaning channels, constructing cutoffs to increase the local slope, constructing flow-control structures to reduce and control the local channel width, and constructing relief channels to improve flow capacity at the crossing. Except for relief channels, these measures are intended to increase the sediment transport capacity of the channel, thus reducing or eliminating problems with aggradation.

Another technique that shows promise is the submerged vane technique developed by the University of Iowa. The studies suggest that the submerged vane structure may be an effective, economic, low-maintenance and environmentally acceptable sediment-control structure with a wide range of applications (HEC 20 *(15)* and Reference *(22)*).

8.8 STREAM CLASSIFICATION

An expert system for stream classification was developed as part of NCHRP Project No. 15-11A, BRISTARS (References *(20)*, *(21)*). The purpose of the stream classification system is to assist BRI-STARS' users in assessing stream stability and in choosing the appropriate sediment transport equation. Stream morphology and related channel patterns are directly influenced by the width, depth, velocity, discharge, slope, roughness of channel material, sediment load and sediment size. Changes in any of these variables can result in altered channel patterns. The methods utilized in the expert system are predicated on bed material sediment size, stream channel slope and discharge. Streams with silt, clay, cobbles, boulders or bedrock as the dominant bed material are classified using Rosgen's method. Sand and gravel bed streams are classified using empirical pattern thresholds and theoretical techniques. Lane, Osterkamp, Leopold and Wolman, Schumm, Fredsoe, Parker and Bray are the methods available to classify sand and gravel bed streams. In the sand and gravel sizes, the user must first determine the size range of the sediment forming the channel bed. Then, the most appropriate method should be selected based upon a comparison of the similarity of hydraulic and sediment parameters at the field site and the particular classification technique. The other methods should only be used for comparison.

David L. Rosgen (References *(23)*, *(24)*) developed a system for classifying streams that is delineated initially into major, broad, stream categories of A – G as shown in Table 8-6. At this level, which Rosgen refers to as level I, the classification system uses the entrenchment ratio, sinuosity, width/depth ratio and the channel slope as the delineative criteria for classifying a river as follows:

- The entrenchment ratio is the ratio of the width of the flood-prone area to the bankfull surface width of the channel.
- The flood-prone area is defined as the width measured at an elevation that is determined at twice the maximum bankfull depth.

- The width/depth ratio is the ratio of bankfull channel width to bankfull mean depth.
- The bankfull mean depth is the bankfull area divided by the bankfull channel width.
- Sinuosity is the ratio of stream length to valley length, and it can also be described as the ratio of valley slope to channel slope.

TABLE 8-6 — Summary of Delineative Criteria for Broad-Level Classification

Stream Type	General Description	Entrenchment Ratio	W/D Ratio	Sinuosity	Slope	Landform/Soils/Features
Aa+	Very steep, deeply entrenched, debris transport streams.	< 1.4	< 12	1.0 - 1.1	> 0.10	Very high relief. Erosional, bedrock or depositional features; debris flow potential. Deeply entrenched streams. Vertical steps with deep scour pools; waterfalls.
A	Steep, entrenched, cascading, step/pool streams. High energy/debris transport associated with depositional soils. Very stable if bedrock or boulder dominated channel.	< 1.4	<12	1.0 -1.2	0.04 - 0.10	High relief. Erosional or depositional and bedrock forms. Entrenched and confined streams with cascading reaches. Frequently spaced, deep pools in associated step/pool bed morphology.
B	Moderately entrenched, moderate gradient, riffle dominated channel with infrequently spaced pools. Very stable plan and profile. Stable banks.	1.4 - 2.2	> 12	> 1.2	0.02 - 0.039	Moderate relief, colluvial deposition and/or residual soils. Moderate entrenchment and width/depth ratio. Narrow, gently sloping valleys. Rapids predominate with occasional pools.
C	Low gradient, meandering, point-bar, riffle/pool, alluvial channels with broad, well-defined floodplains.	> 2.2	> 12	> 1.4	< 0.02	Broad valleys with terraces in association with floodplains, alluvial soils. Slightly entrenched with well-defined meandering channels. Riffle/pool bed morphology.
D	Braided channel with longitudinal and transverse bars. Very wide channel with eroding banks.	N/a	> 40	n/a	< 0.04	Broad valleys with alluvial and colluvial fans. Glacial debris and depositional features. Active lateral adjustment with abundance of sediment supply.
DA	Anastomosing (multiple channels) narrow and deep with expansive, well-vegetated floodplain and associated wetlands. Very gentle relief with highly variable sinuosities. Stable streambanks.	> 2.2	Highly variable	Highly variable	< 0.005	Broad, low-gradient valleys with fine alluvium and/or lacustrine soils. Anastomosed geologic control creating fine deposition with well-vegetated bars that are laterally stable with broad wetland floodplains.
E	Low gradient, meandering riffle/pool stream with low width/depth ratio and little deposition. Very efficient and stable. High meander width ratio.	> 2.2	< 12	> 1.5	< 0.02	Broad valley/meadows. Alluvial materials with floodplain. Highly sinuous with stable, well-vegetated banks. Riffle/pool morphology with very low width/depth ratio.
F	Entrenched meandering riffle/pool channel on low gradients with high width/depth ratio.	< 1.4	> 12	> 1.4	< 0.02	Entrenched in highly weathered material. Gentle gradients with a high width/depth ratio. Meandering, laterally unstable with high bank-erosion rates. Riffle/pool morphology.
G	Entrenched “gully” step/pool and low width/depth ratio on moderate gradients.	< 1.4	< 12	> 1.2	0.02 - 0.039	Gully, step/pool morphology with moderate slopes and low width/depth ratio. Narrow valleys or deeply incised in alluvial or colluvial materials; i.e., fans or deltas. Unstable with grade control problems and high bank erosion rates.

- Slope is the water surface slope and can be determined by measuring the difference in water surface elevation per unit stream length. At the broad level classification, the slope can be estimated from USGS quadrangle maps.

The broad level classifications are then segregated into sub-classes based on the dominant bed material. The stream types are assigned numbers related to the size of the dominant bed material such that 1 is bedrock, 2 is boulder, 3 is cobble, 4 is gravel, 5 is sand and 6 is silt/clay. This produces 41 major stream types as shown in Table 8-7. Rosgen's classification system also incorporates a continuum concept. The continuum concept is applied where delineative criteria values outside the normal range are encountered but do not warrant a unique stream type. This yields the following sub-categories based on slope — a+ (steeper than 0.10), a (0.04 – 0.099), b (0.02 – 0.039), c (flatter than 0.02), and c- (flatter than 0.001). The continuum concept also allows the entrenchment ratio and sinuosity to vary by ± 0.2 unit, and sinuosity can vary by ± 2.0 units. The expanded classification system that incorporates the continuum concept is shown in Table 8-8. Rosgen refers to the classifications shown in Tables 8-7 and 8-8 as level II.

TABLE 8-7 — Rosgen's River Classification System

		Rosgen's River Classification								
Bed Material	Bedrock	A1a+	A1	B1	C1				F1	G1
	Boulder	A2a+	A2	B2	C2				F2	G2
	Cobble	A3a+	A3	B3	C3	D3		E3	F3	G3
	Gravel	A4a+	A4	B4	C4	D4	DA4	E4	F4	G4
	Sand	A5a+	A5	B5	C5	D5	DA5	E5	F5	G5
	Silt/Clay	A6a+	A6	B6	C6	D6	DA6	E6	F6	G6
Criteria	Entrenchment	<1.4	<1.4	1.4 - 2.2	>2.2	N/A	>4.0	>2.2	<1.4	<1.4
	Sinuosity	1.0 -1.1	1.0 - 1.2	>1.2	>1.2	N/A	Variable	>1.5	>1.2	>1.2
	Width/Depth	<12	<12	>12	>12	>40	<40	<12	>12	<12
	Slope	>0.10	0.04 - 0.099	0.02 - 0.039	<0.02	<0.04	<0.005	<0.02	<0.02	0.02 - 0.039

TABLE 8-8 — Rosgen's Stream Classification System

	Single Thread Channels														Multiple Channels			
Entrenchment Ratio[1]	Entrenched (< 1.4)						Moderately Entrenched (1.4 – 2.2)			Slightly Entrenched (> 2.2)					N/A			N/A
Width/Depth Ratio[2]	Low (< 12)				Moderate – High (> 12)		Moderate (> 12)			Very Low (< 12)		Moderate – High (> 12)			Very High (> 40)			Low (< 40)
Sinuosity[1]	Low (< 1.2)		Moderate (> 1.2)		High (> 1.2)		Moderate (> 1.2)			Very High (> 1.5)		High (> 1.2)			Low (< 1.2)			Low - High (1.2-1.5)
Broad Class	A		G		F		B			E		C			D			DA
Slope Range	> 0.10	0.04 to 0.099	0.02 to 0.039	<0.02	0.02 to 0.039	< 0.02	0.04 to 0.099	0.02 to 0.039	< 0.02	0.02 to 0.039	< 0.02	0.02 to 0.039	0.001 to 0.02	less than 0.001	0.02 to 0.039	0.001 to 0.02	less than 0.001	less than 0.005
CHANNEL MATERIAL: Bedrock	A1a+	A1	G1	G1c	F1b	F1	B1a	B1	B1c			C1b	C1	C1c-				
Boulders	A2a+	A2	G2	G2c	F2b	F2	B2a	B2	B2c			C2b	C2	C2c-				
Cobbles	A3a+	A3	G3	G3c	F3b	F3	B3a	B3	B3c	E3b	E3	C3b	C3	C3c-	D3b	D3		
Gravel	A4a+	A4	G4	G4c	F4b	F4	B4a	B4	B4c	E4b	E4	C4b	C4	C4c-	D4b	D4	D4c-	DA4
Sand	A5a+	A5	G5	G5c	F5b	F5	B5a	B5	B5c	E5b	E5	C5b	C5	C5c-	D5b	D5	D5c-	DA5
Silt/Clay	A6a+	A6	G6	G6c	F6b	F6	B6a	B6	B6c	E6b	E6	C6b	C6	C6c-	D6b	D6	D6c-	DA6

[1] Values can vary by ±0.2 unit.
[2] Values can vary by ±2.0 units.

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